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A Quantitative Study of Chromatic Adaptation

BY

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PREFACE

The following study as here presented was submitted to the Faculty of Bryn Mawr College in May, 1923, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. It is one of a series of studies dealing with the selectiveness of the eye's response that is being conducted in the Bryn Mawr College laboratory. This investigation would have been impossible without the constant supervision and advice of Dr. C. E. Ferree, to whom the writer wishes to express her gratitude. She is also greatly indebted to Dr. Gertrude Rand for valuable suggestions in the experimental work.

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I. INTRODUCTION

This is one of a series of investigations dealing with the selectiveness of the eye's response, achromatic and chromatic, that is being conducted in the Bryn Mawr College laboratory. The complex nature of these responses does not seem to have been fully realized by investigators in physiological and psychological optics. The influence of many of the factors which cause variability in the responses of the eye can be eliminated by proper attention to experimental controls. There are some, however, whose influence is grounded in the nature of the retina as a receptor, and cannot be eliminated by any effort at control. Upon the effect of these must the ultimate law of the psychophysical relation in vision be based. In terms of the Fechner formulation of this relation, the intensity of sensation is a regular function of the intensity of the stimulus. Indeed the Fechner law of the relation of response to stimulus rivals in simplicity the oldest of the laws for the action of light on the photographic plate, the Bunsen-Roscoe law: $S = I \times T$, in which S represents the blackening of the plate, I the intensity of light, and T the time of action on the plate. Knowledge of the action of light on the photographic plate, however, soon progressed beyond this formulation, and after a few years the Bunsen-Roscoe law was discarded as inadequate. Similar progress has not been made with regard to the eye's response to light. The Weber-Fechner law is still accepted in the subjects of physiology, psychology and physics as a general expression for the relation of sensation to its stimulus. It should not be necessary at this time to point out the fallacy of this law as applied to visual sensation. Visual sensation is a complicated function of at least four interacting variables: wave-length and intensity of light, time of action on the eye, and the condition of general brightness adaptation. That is, when the wave-length and time of exposure are held constant, the eye is selective in its response to intensity; when wave-length and intensity are held

constant, it is selective to time of exposure; and when intensity and time of exposure are held constant it is selective to wave-length. Moreover, this selectiveness changes in its amount with change in the condition of general brightness adaptation. It is safe to predict that when the relation of intensity of sensation to intensity of light is finally and correctly written for vision, intensity of sensation will not be expressed as a regular function of one variable, the intensity of the stimulus, as it is in the Fechner formulation, but as an irregular function of four interacting variables: wave-length and intensity of light, time of action on the eye and the eye's condition of general brightness adaptation. This is true not only of the responses of the eye but also of all of the other effects of light that have been used in the attempt to measure light intensities, with the exception of the thermal effect. No one would think, for example, of attempting to express the response of the selenium cell, the photoelectric cell or the photographic plate as a function of one variable; yet the eye is admittedly more complex in its responses than any one of these reactors.

The purpose of this study has been to investigate one phase of the eye's selectiveness of response to two of these variables, namely, to time of exposure and state of adaptation. As a function of time of exposure, the responses of the eye show in general the following characteristics: They rise to a maximum through a comparatively short interval of time, then decay or die away to a minimum, at first rapidly, then more slowly. The rate of change in both regards is an irregular function both of wave-length and of intensity; and in addition the present study shows that both rate and amount of decay are irregular functions of the condition of general adaptation. This progressive decay or decrease of the response for the achromatic sensation has been called by Aubert, adaptation. Although the fitness of this term in general to express the post-maximum phase in the eye's selectiveness of response may be open to question, it will be used for convenience in this study. In case of the physical instruments which respond to light, the decay of response with time is often called a fatigue effect. The use of the term adaptation would find little favor as

applied to these instruments. The term fatigue has been used by Fechner, Helmholtz, and others also to characterize the decay of the sensory response.

In the study of the phenomena of adaptation, two possibilities of attack may be mentioned. The course of sensation may be traced in just noticeably different steps from maximum to minimum; or a rating may be made of the change in the eye's power of response or sensitivity. Although they serve somewhat different systematic and practical purposes, both are important. The tracing of the actual course of sensation doubtless has the greater practical usefulness. It is of especial importance to photometry, to colorimetry, to lighting, in relation to the eye, to the arts, and to all of the applications of the testing of the color sense.

Three methods have been devised in this laboratory for tracing both the rise and the decay of sensation. By these methods the courses of sensation may be determined in just noticeably different steps from minimum to maximum in the rise and from maximum to minimum in the decay. A brief description of the most convenient of these methods may not be out of place here to show how the problem may be attacked from this point of view.*

The determination in the use of this method may be made by means of a rotary tachistoscope with an exposure disc compounded of two pairs of discs having radii of different lengths. These discs are mounted on the axle of the tachistoscope and their position is so adjusted that the circular edge of the smaller set of discs bisect vertically the observation field. These halves, right and left, form the comparison fields for the determination of the sensation curves. This determination may be made as follows: The smaller set of discs is closed completely and the larger is opened by a series of adjustments, until with a given speed of rotation of the discs a just noticeable sensation is aroused. For the next observation the smaller set of discs may be given this value of opening and the opening of the larger pair be increased

* This method, devised by Rand, has been used by Rand and Ferree in determining the rise of sensation from the threshold to the maximum. It and two additional methods, devised by Ferree, have also been described by Bills, and used by her in a study of the comparative merits of methods for determining the rise of sensation. Psych. Monograph, No. 127, p. 99.

until a just noticeable difference in sensation is obtained. The series is continued, the comparison opening for one observation being made the standard for the next, until a value of exposure is obtained no further increase of which causes a noticeable increase in the sensation aroused by the comparison field. This is accepted as the optimum value of the sensation and the sensations produced by other exposures are rated in terms of their number of just noticeable differences from zero. Further increase in length of exposure will cause a decrease in the sensation aroused by the comparison field and a continuation of the series beyond this point will give the values of the just noticeable difference needed to plot the other half of the curve which represents the temporal course of sensation, rise, and fall.

A study by this or a similar method of the selectiveness of the response of the eye to time of exposure, including both the rise and decay of sensation for the same observer or observers, would be very desirable and important. The time and labor involved, however, in making the determinations for any considerable range of intensity of light and conditions of experimentation, would have far exceeded the time limit imposed upon this study. Also the apparatus required to give the automatically controlled and timed exposures needed to trace the relatively slow process of decay presented difficulties which could not be overcome in time for the present work. From the standpoint of feasibility, therefore, and the range of conditions that could be studied, it was decided to make the first attack on the quantitative study of the adaptation process, in terms of loss of sensitivity.

If a study of loss of sensitivity is to be made quantitative up to the standard used in rating the sensitivity of the physical recording instruments, it must conform to the following requirement: both terms involved in the expression for sensitivity, amounts of response and amount of stimulus, must be numerically comparable. The amounts of response that have been used in the determination of sensitivities are equal amounts, equal sense differences, the threshold, the just noticeable difference, and the average deviation in any one of these determinations, called the average error. Equal amounts and equal sense differences are

the only ones which are with certainty numerically comparable. The remainder are open to question.

In the discussion of methods and possibilities of classification or treatment in new fields, it is often helpful to examine the work in older fields for patterns or principles. In this regard the sense organ may be considered as a recording instrument with the threshold and just noticeable differences as the smallest assignable divisions on its scale. The question whether or not as amounts of response they are equal in the different parts of the scale for the same instrument or sensorium depends, to use again the physical analogy, upon the ability to estimate or read the scale in its different parts. In Fechner's thinking they were judged directly in terms of a mental or memory pattern and are therefore theoretically equal within the limits of precision of the performance. So conceived, the just noticeable difference is often called the Fechner J.N.D., as distinguished from a later conception according to which this quantity is not judged directly in terms of a standard or pattern, but is the end point or result of a series of determinations in which all of the judgments are either equality or difference. That is, in terms of this conception, only the judgment of equality and difference are possible. Just noticeable differences cannot be judged directly. They must be inferred from a series of judgments of equality and difference grouped or arranged with reference to the end to be attained. They are not equal in principle, therefore, by virtue of having been judged in comparison with a common or fixed standard. Their equality, if accepted at all, must be accepted only as an inference from the method employed. In practice the question will perhaps always remain without an answer because of our inability to compare one of these divisions with another directly or in terms of a fixed standard, as is possible in case of the divisions in a linear or other physical scale. However, the need to rate and compare in numerical terms, in the great number of cases in which equal amounts of response, directly judged, cannot be used, will probably force us to continue to use the threshold and the just noticeable difference in the rating of sensitivity even though their use may not fully satisfy the quantitative requirement.

In planning this study two methods have been considered for determining the progressive loss of sensitivity of the eye during the course of its adaptation to color: one based on equal amounts of response (sometimes called the method of equivalents), the other upon threshold amounts. In both cases the amounts of light required to arouse these responses should be measured in energy terms. This is necessary to satisfy the second condition of the quantitative requirement, namely, that the amounts of stimulus shall be numerically comparable. A well known example of the use of equal amounts of response in a quantitative rating of sensitivities is found in the visibility curve, which is a sensitivity curve for the achromatic response of the eye. In this curve a graphic representation is made of the reciprocals of the light energies at different points in the spectrum which are required to arouse equal achromatic or photometric responses. Thus the sensitivity at any one point in this curve can be compared numerically with that at any other point. That is, the method of making the determinations satisfies fully the quantitative requirement. Obviously the principle involved in making these determinations can be applied to the determinations of sensitivity in any case where the judgment of equal amounts of response can be made within acceptable limits of precision. Such a judgment is difficult in case of the chromatic response in the presence of hue difference. However, equal saturations of the same hue are easily judged. This is the type of judgment that would have to be employed in the use of equal amounts of response in tracing the loss of sensitivity in chromatic adaptation. The method might be applied in the following way: Two fields, each receiving half of the beam of light, would serve respectively as stimulus and measuring field. The eye could be exposed to the stimulus field for the desired length of time and at the end of this time the measuring field could be exposed and a judgment made as to the relative saturation of the sensations aroused by the two fields. If they appeared unequal the light in the measuring field could be changed and the adjustment made again. The adjustments should be continued until equal saturations are obtained. The sensitivities of the parts of the retina receiving the light from the two fields, therefore,

could be expressed as the reciprocals of the amounts of light required to produce the equal amounts of chromatic response. If the determinations were made for a number of exposure times, a series of values would be obtained which express the relation of the sensitivity of the fatigued or color adapted part of the retina to that of the adjoining nonfatigued area. From these values, in turn, a series of values or percentages may be determined which express quantitatively the rate of loss of sensitivity of the fatigued part of the retina for the different intervals of exposure used. In spite of the fact that this method fully satisfies the requirements of a quantitative determination of sensitivity, the following objections may be noted which make it infeasible to use for the study of chromatic adaptation: (1) Although the part of the retina receiving the image of the measuring field need not have the same sensitivity as that receiving the image of the stimulus field, its use in tracing the loss of sensitivity to that field presupposes that its sensitivity be maintained constant throughout the work. That is, its sensitivity must serve as the fixed standard against which to rate the loss of sensitivity of the part of the retina which is being fatigued. It is quite obvious that in any adaptation series this constancy of sensitivity is difficult if not quite impossible to attain, particularly for determinations made under light adaptation, because while the stimulus area is changing in sensitivity during the period of exposure employed, the measuring area must also change in sensitivity. That is, in such experiments the ordinary presensitizing precautions which are used to control sensitivity for short exposures of a fixed interval, by means of preëxposures, do not accomplish this purpose for exposures varying from one second to several minutes. Obviously the preëxposure would have to be to some neutral surface. For example, if the preëxposure were to black, a white after-image of a brightness varying with the length of the preëxposure would be added to the sensation aroused by the colored light on the measuring field at the time of making the saturation match with the stimulus field. The effect of this white after-image would be to exert a strong inhibiting or cancelling action on the color component of the sensation, by amounts varying with the brightness

of the after-image and the color used. Thus the response and correspondingly the color sensitivity of the measuring area at the time of making the match with the sensation given by the stimulus area would deviate from constancy by amounts varying with the different lengths of exposure used in the adaptation series. If the preëxposures were to white, a similar effect would be obtained but less marked in amount because of the weaker inhibitive action of the black after-image upon the color. The closest approximation to constancy would be obtained with a gray of the brightness of the color at the close of the particular period of exposure for which the determination was made; but even this precaution would not be entirely effective because, although it would prevent the development of a brightness after-image on the measuring surface, it would result in a variable state of achromatic sensitivity due to the different lengths of preëxposures and this variable achromatic sensitivity would affect correspondingly the relation and proportion of the achromatic to the chromatic component of the color sensation aroused by the measuring field. To that extent the chromatic response and sensitivity, at the time of matching the saturation of the stimulus field with that of the measuring field, would be altered. Moreover, any condition of experimentation or attempt at control that would involve the development of an achromatic after-image on the measuring field or a change in the achromatic sensitivity in the corresponding area of the retina would produce a different effect for the different colors and thus render inaccurate any attempt at a comparison of the rate of loss of sensitivity for the different colors. There are two reasons for this: (a) the difference in the brightness of the colors at the time the match is made; and (b) the difference in the amount of the inhibitive action of the achromatic after-image on the chromatic component of the sensation for the different colors. (2) A possible second cause of inconsistency of sensitivity of the measuring area of the retina is the stimulation of the contiguous area for periods of time varying from a few seconds to several minutes with the same color to which it is to react as a measuring instrument. Whether this would produce an effect has not as yet been determined directly. However, it does not seem safe to assume

from what is known of the interacting influence of adjoining areas of the retina upon each other's powers of response that there is an absence of effect, particularly under the usual conditions of time of exposure used in an adaptation series. (3) A quantitative comparison of the rate of loss of sensitivity for different wave-lengths of light could be made by this method only in case the same wave-lengths and intensity were used in the measuring field throughout. In the cases in which the light in the stimulus field differed in composition from that of the measuring field, this would require a judgment of equal saturations between lights differing in hue. It is doubtful whether such a judgment can be made within acceptable limits of precision.

All things considered, it has been deemed safer to use a threshold method of rating sensitivities in this series of experiments. Intervals of stimulation have been chosen with special reference to the rate of loss of sensitivity at different times in the course of adaptation. Immediately at the close of each of these periods, the intensity of the beam of light was cut down to present a field the intensity of which was adjusted in a number of trials, ascending and descending series, to give a just noticeable chromatic sensation. Sensitivity was expressed as the reciprocal of the energy of the light required to arouse the threshold value of sensation. Within the limits of the approximation made then, in considering the thresholds as equal amounts of response, this method of making the determination permits of a numerical rating of the loss of sensitivity not only for a given color but also of a numerical comparison of the rate of loss for the different colors. The details of the method of making the determinations will be given in a later chapter.

The determinations were made under the following conditions:

(1) The lights were made photometrically equal at three intensities: 12.5, 25, and 40 meter-candles. The determinations made under these conditions serve a two-fold purpose: (a) they give us the effect of photometric intensity on chromatic adaptation; and (b) they provide a knowledge of the comparative rates of adaptation for color under the conditions which prevail in

lighting, namely, equal photometric intensities. The latter feature was a very important incentive for the investigation.

(2) In another series of investigations, the colors were made equal in saturation. These determinations are important particularly to colorimetry and in the fields to which that type of rating or specifying color is applied.

(3) In a third set of investigations, the lights were made equal in energy. These determinations alone give results which express the true selectiveness of the adaptation process to time of exposure.

The ways in which the stimuli have been equalized include, it will be noted, all the ways, objective and subjective, in which the amount of colored light may be specified. This served as a more general reason for conducting the experiment under the conditions given above.

In case of each of the above investigations, the determinations were made both under light and dark adaptation. The work under light adaptation was done in an optics room designed especially to give uniform illumination. All the light illuminating this room came from a skylight with a diffusion sash of ground glass swung beneath. The horizontal component of light at the point of work was maintained constant at 214 foot-candles. The vertical component was 221 foot-candles. In the work under light adaptation the brightness of the surrounding field was made in every case the same as that of the color.

It might be well to inquire a little further as to just what is accomplished by this method of tracing the loss of sensitivity of the adapting eye. Again the problem can best be discussed in a comparative way. The eye is similar to a physical recording instrument the sensitivity of which varies not only for the different parts of the intensity scale for a given wave-length and time of exposure but also changes irregularly at each point for different times of exposure. In our quantitative attack on the problem, we are in effect calibrating the sensitivity with reference to length of exposure at the first point in the scale, the threshold for the different intervals of exposure used in the adaptation series. For example, the series might very well be called a one-point calibration series for lengths of exposure longer than is required for the

eye to give its maximum response. Correspondingly, the curves plotted may be considered as calibration curves for these conditions of exposures. They would undoubtedly be so considered in case of a physical instrument. The effect on the sensitivity in other parts of the scale remains undetermined. If we were to use the method of equivalents in tracing the sensitivity, the calibration would also be a one-point calibration but the serial position of the point in the scale would be continually changing. That is, the calibration each time would be made for that point in the scale representing the total response of the eye to the given amount of light, not its threshold for light of that wave-length.

II. HISTORICAL

Although it has long been known that a continuous action of colored light on the eye causes changes in the sensation aroused, very few scientific investigations have been conducted with regard to these changes. No attempts at measurement have been made, for example, that can be considered as quantitative. The work done has been, for the greater part, a demonstration that the phenomenon of decay exists and a description of the changes that take place in the process of decay. As late even as 1903, Broca and Sulzer (1) claimed that after an exposure of two seconds to colored light a permanent sensation level is reached; moreover, they based important experimental technique on this claim.

The changes which take place in sensation as the result of adaptation are loss of saturation, change in brightness, and change in hue. The more pronounced and important of these are the changes in saturation and brightness. Quantitative work can be done on either of these changes but it must be done upon each separately. In making the investigation by tracing the loss of sensitivity, it is not possible in all cases even to make the study by the same methods. In this study saturation has been chosen as the aspect to be investigated. Thus far there has not been much work even of a descriptive nature on the changes of brightness. In most cases the change in brightness has been mentioned more or less casually or incidentally in the course of a description of the changes in hue and saturation. In this connection, apparently, not even the functional relation between brightness change and hue change, the effect of the achromatic upon the chromatic component of the excitation, has been suspected.

The literature from the standpoint of measurement is brief and unimportant and most of it need be given only a passing mention. Schön's work alone contains the germ of the quantitative idea of treatment. The review will be given under three heads: studies dealing with loss of saturation, studies dealing with changes in

hue, and studies dealing with changes in brightness. Although the first of these types of study should, perhaps, be regarded as of dominant interest and importance, the work on changes in hue and brightness have, in general, been conducted with the better experimental technique.

A. Loss of Saturation

The work on loss of saturation is somewhat difficult to review in any coherent or systematic way. The problem is yet without a definite formulation. Some observers have been content merely to note and give a rough description of the phenomenon, others have been interested in its similarity to color blindness, while still others have been actuated by various theoretical and analytical interests which have sustained no particular relation to each other.

To the first group belong Plateau, Helmholtz, Exner, Nagel, and Aubert. As early as 1834 Plateau (2) observed that if one fixated for a time a small red paper on a black background and then looked at a larger piece of the same paper, a part of the paper corresponding in size to the small piece appeared colorless. In 1866, Helmholtz (3) reported loss of saturation as the result of adaptation for both pigment and spectrum colors. This result was confirmed by Exner (4) for spectrum colors in 1868, and in 1869 Nagel (5) maintained that after continued fatigue to a color all objects appear distorted in color perception. Aubert (6) in 1876 observed the phenomenon in relation to brightness of the surrounding field. He reported that a well illuminated colored surface fixated for one minute through a black tube becomes dark and colorless. He also stated that if a red square 3 mm. x 3 mm. placed on a dark or white background be viewed at a distance of four to five meters or at an angle, the color disappears still more quickly. Dark blue and dark green, he says, lose their color more quickly as the result of adaptation than red.

To the second group belong Bokowa, Ssamujlow, Porter and Edridge-Green, Beck and Burch. In an endeavor to experience the sensations of the red-blind, Maria Bokowa (7), 1868, wore for several hours spectacles fitted with red glass narrowly selective in its transmission. She reported that at the end of this time she

was completely insensitive to red. No statement was made, however, of the intensity of the red light used in the final test for red sensitivity.

A paper on the question of the fatigue of the retina to different colors was read by Ssamujlow (8) at the III Congress der russischen Aerzte zu St. Petersburg, held in 1889. This paper, however, was reported so briefly in the proceedings of the meeting that it is impossible to give an adequate account of the experiments conducted. In order to determine the comparative amounts of fatigue to red, blue and green, Ssamujlow noted the duration of the negative after-image following fatigue to each of the colors. He found an unequal period of persistence for the different colors and concluded that the retina is fatigued most by red, less by green, and still less by blue. Apparently no account was taken in his experiments of the difference in the effect of intensity of light and of the brightness of the projection ground on the duration of the after-images for the different colors. The experiments in general seem to have been conducted without an adequate control of the factors which would produce a differential effect on the duration of the after-image.

In 1898, Burch (9, 10) reported in the proceedings of the Royal Society the results of his observations on temporary color blindness artificially produced. He focussed on the eye direct sunlight which had been passed through various colored media. The colors used were violet, green, purple, and red. He claims to have experienced a complete loss of color sensitivity, the time for the production of which varied with the color of light employed. Again the intensity of light used for testing the completeness of the loss of sensitivity is not given. In a later study he repeated the experiments, using moonlight instead of sunlight as the source of the stimulus light. He reports that under this diminished intensity of fatiguing light, all power was lost for sensing green and blue but not for red.

Beck (11) became interested in chromatic adaptation through an observation of the effect of achromatic adaptation on the chromatic response. After reading under intense illumination, he noticed that red appeared black or brown. He also observed that

after fixating a sunlit area the power to distinguish between red and green was lost and mixtures of other colors with red and green appeared poorly saturated. He became so interested in these observations that he experimented also with spectrum light. He found, depending upon the degree of fatigue, that the hue of the fatiguing color was either not visible or was diminished in saturation.

Porter and Edridge-Green (12), in 1912, ascertained the appearance of pure spectrum colors after the eye had been fatigued by light of a known wave-length: A portion of the retina of one eye was fatigued by fixating a horizontal spectrum for twenty seconds. The eye was then turned to a larger horizontal spectrum projected on a screen. Since the after-image band resulting from the preceding stimulation was smaller than the spectrum on the screen, the sensation from the fatigued areas of the retina could be compared with those from the surrounding nonfatigued areas. Fatigue to red, 654–675 mμ was found to cause only a slight loss of sensitivity to that color, but the spectrum blue, 445–455 mμ, could no longer be sensed as color. Later, 1913, Edridge-Green (13) makes the more positive statement that parts of the spectrum appear as colorless, after a period of adaptation sufficiently prolonged. He also reports that temporary color-blindness to spectrum yellow can be produced by general adaptation for a period of twenty minutes to the light of a room illuminated by a sodium flame.

As an outgrowth of his interests in the comparative merits of the Helmholtz and Hering theories, Brückner (14), at the suggestion of Hering, made a study of saturation changes as the result of adaptation, chromatic and achromatic. Thirteen colors were used as reacting stimuli. The eye was fatigued to seven colors, to grays of the brightness of these colors, to white and to black. Hering papers were used throughout the experiments for the fatiguing as well as the reacting colors. A wave-length specification of the dominant hue was given for some of the colors but there was no attempt at a specification of intensity or of composition, spectrophotometric or colorimetric. The fatiguing and reacting lights were presented to the eye by means of the Helm-

holtz " Spiegelapparat " (Physiol. Optik, p. 350). The procedure was as follows: The fatiguing stimulus was placed at A, Fig. 1, and light from this was reflected from a plate glass, S, to the eye of the observer at E. After the fatigue period, usually from 10

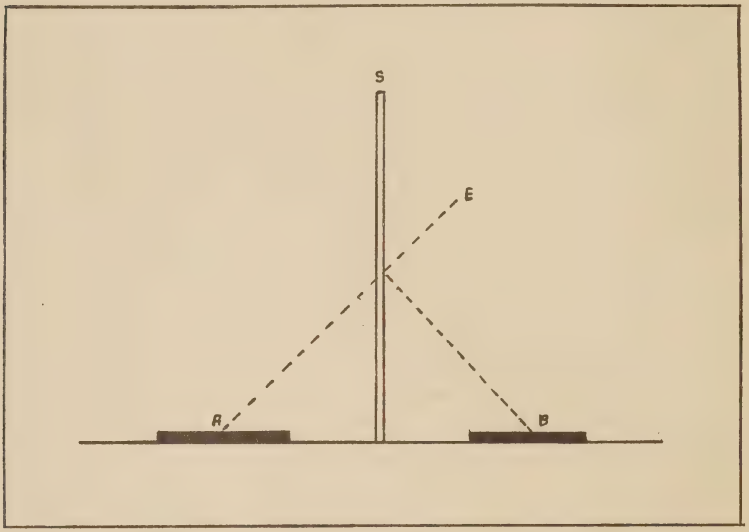

FIG. 1. Brückner's apparatus.

to 15 seconds, A was covered and B, the reacting stimulus, was uncovered. The position of the observer's eye was such that the transmitted light from B and the reflected light from A fell on the same retinal area. Any fatigue effects, therefore, due to a previous stimulation by A, produced a change in the appearance of B. Stimulus A was made up of two parts: one half was of colored paper and the other half, at the option of the experimenter, was white, black, or gray of the brightness of the color. B was a homogeneously colored surface.

The results were expressed in terms of whether the saturation of the reacting color was affected more by the previous exposure of the eye to the chromatic or to the achromatic half of the stimulus field. The changes in the chromatic half of the stimulus field as the result of fatigue were not recorded.

The following table is quoted to show the results of his inves-

tigation. In this table the color of the chromatic half of the stimulus field is indicated in the first vertical column; the color of the reacting field in the first horizontal column. The quality of the neutral half of the stimulus field is recorded in the second

TABLE I

Showing the results of Brückner's experiment.

		Red	Yellow-red, 664 mμ	Orange, 622 mμ	Gold-yellow, 580 mμ	Green-yellow, 575 mμ	Yellow-green, 550 mμ	Green, 500 mμ	Blue-green, 483 mμ	Blue, 470 mμ	Blue-violet, 463 mμ	Red-violet, 459 mμ	Blue-purple	Red-purple
Neutral red	a		—	—	+	+	+	+	+	:+	+?	?+	—	—
	b		—	—	?+	+	+	+	+	:—	—	—	—	—
	c		—	—	—	+	+			:—	—	—	—	—
Yellow red, 664 mμ	a			—	+	+	+			+	+	+	?—	
	b			—	—	?+	+			+	?	?	—	
	c				—	—	?—			?	—	?—		
Green-yellow, 575 mμ	a	+	+	?	—		?	+?	+	+	+?	+	+	+
	b	·?	?	—	—		?	?	?	+	?+	?	?	?
	c													
Yellow-green, 550 mμ	a	+	+	+	?				+	+		+		
	b	?	?	?	?				—	?		?		
	c	?	?	—	?				—	?—		?		
Neutral green, 500 mμ	a	+	+	+	+		—		?	+	+	+	+	+
	b	?+	?	+	+		—		—	?	?	?	?	+
	c		?	?	?				—	?	?	?		
Blue, 470 mμ	a	+	+	+	+	+	+	—	—		—	?	+	+
	b	?	?	?+	+	+	?	—	—		—	—	?	—
	c	—	?	?	+		—	—	—				—	
Red-violet, 459 mμ	a	+	+	+	+	+	+	+	—	?	—			+
	b	—	+?	—?	?	+	?	—	—	—	—			—
	c	—	—	—	—		—	—	—					—

vertical column: black is indicated by "a"; white by "c"; and the grays of the brightness of the color by "b." The remaining vertical columns show the results of the comparative observations. A minus sign is used to indicate that the reacting color appeared less saturated when fatigued by the chromatic than when fatigued by the achromatic half of the stimulus; a plus sign to indicate the converse result.

In 1920 an investigation was made by Sheppard (15) to ascertain the time of adaptation required to render the eye insensitive chromatically to different pigment and spectrum colors. His determinations fell under four headings: (1) general adaptation to pigment papers; (2) foveal adaptation to pigment colors, illuminated (a) by "mild daylight," and (b) by light from a type C_2

Mazda lamp; (3) foveal adaptation (a) to colors of a prismatic spectrum, (b) to these colors equalized in brightness, and (c) to these colors equalized in saturation; and (4) adaptation to colors of high intensity obtained by the use of filters.

In his first set of experiments large sheets of pigment papers were used and also discs composed of 180° of color and 180° of black and white. These colored surfaces of different saturation were illuminated by the direct light from a window. The observations were made from 2 to 4:30 P.M. on clear days during the months of July and August. That a wide range of illumination occurs between these hours even on selected days is well known to all who have had experience in measuring the daylight illumination of rooms; yet the mean variation in the time required to bring the colors to zero saturation in his experiments was sometimes not larger than 1 to 2 per cent. Also the agreement of results for different observers was remarkably close. The average time required to bring about complete adaptation for the sheets of pigment papers was, for yellow, 45.9 seconds; for green, 50.6 seconds; for red, 194.1 seconds; and for blue, 220 seconds. For the series with reduced saturation (180° of color and 180° of black and white), these intervals were respectively 23.4, 23.7, 98.2, and 121.3 seconds.

The second series of experiments was conducted at a medium intensity of illumination, produced by drawing the white curtains over the windows of the room in question. This should have given a more diffuse illumination and one less subject to extremes of local change, yet these conditions were found to give such unsatisfactory results that the experiments were discontinued and artificial illumination was substituted. For this purpose Mazda type C_2 lamps were used. The following specification was given: "The illumination was produced by three 75-watt, 110-volt, Edison-Mazda daylight bulbs; it was equal to 212.4 c.p. at a distance of 2.5 m. from the stimulus-color and a distance of 1 m. above and a little in front of O." It is somewhat difficult to tell just what this specification means because of the confusion of photometric units; also the numerical values assigned seem to be impossible. Moreover, there appears to be some error or con-

fusion in the statement of the size of the stimulus. The statement is made that the experiments were planned for foveal adaptation; yet the stimuli were described as circular discs 100 cm. in diameter, 225 cm. from the eye. Even if one considered the breadth of the discs as 100 mm. the visual angle subtended at the eye would be 2° 32′ which is larger than the fovea.

In his third series of experiments the following spectrum lights were used: red, 740–770 mμ; yellow, 545–575 mμ; blue-green, 495–525 mμ; blue, 440–470 mμ, and violet, 405–435 mμ. Again the stimulation was called foveal, but a computation of the visual angles from the data given shows values ordinarily considered extra-foveal. Three sets of conditions were employed. The stimuli were used with the brightness distribution as it occurs in the spectrum employed; they were equalized in saturation; they were equalized in brightness. No indication is given as to how the stimuli were equalized in brightness nor is the value of the brightness at which all were equalized stated. The only specification of intensity given is that " The amount of light that entered the collimator of the spectroscope was 61.4 c.p." It is scarcely necessary to point out that a specification of the amount of light entering the slit of the spectroscope would be of little value for the purpose of his experiments even had it been made in terms of the appropriate photometric units. The rating should have been made at the stimulus field or at the eye. Since more nearly equal intervals of time were required to produce complete adaptation to all of the colors when equalized in saturation than when equalized in brightness, Sheppard concluded that saturation is the prime determinant in the rate of chromatic adaptation. In case of one field size, 3 mm., the times required were very nearly the same for all of the colors but this was not true for the field sizes, 4.5 mm., or 2 mm.

The present writer by no means obtained equal rates of adaptation for colors equalized in saturation. In her experiments, however, saturations were equalized without the admixture of white light while in Sheppard's experiments white light was added to each of the colors until they matched the violet of his spectrum in saturation. That is, in his experiment, as a result of adding

the white light, all of the following factors were varied simultaneously: composition, purity, physical intensity, brightness, hue, and saturation. On the principle of concomitant variation then it could scarcely be claimed that the results obtained were due to the variation of one factor alone, saturation. The analytical problem attempted by Sheppard is at best scarcely feasible; at least not by the method used by him. It is too difficult to vary one of the factors with the degree of separation needed. About all one can hope to do is to hold one or perhaps two of the factors constant and vary the remainder in some relation or other. Some conclusion might perhaps be arrived at as to the relative importance of factors by combining a method of experimental variation, granting the possibility of rating the amounts of variation of each of the factors, with some method of partial correlation.

Apparently Sheppard's object in his last series of experiments was to determine whether colors of great intensity produce complete chromatic adaptation in the fovea. He had not found this to be true with stimuli of small area, due, he believed, to the disturbing effect of eye-movement on the adaptation to small stimuli. This disturbing effect was particularly important for high intensities because of the long periods required to adapt to such intensities and the greater incentive to involuntary eye-movement under the excessive stimulation produced by the high intensities. He sought to overcome this difficulty by using large areas as stimulus field and small areas as reacting field. Filters were employed to give the large areas used as stimulus field; the reacting lights were taken from the spectrum. The exact conditions used are somewhat difficult to understand from the description. For the stimulus-light colored gelatines red, yellow, blue-green, blue, and violet, were fitted into goggles and light from a projection lantern was passed through these filters. "The focus of the light was adjusted to fall within the eye." The observer was directed to fixate this light until all of the color disappeared after which he was to remove the goggles and "fixate the spectroscope." Again there is confusion as to the photometric specifications. With reference to the light from the lantern the statement is

made, "The actual amount of light focussed by the lens was about 6,200 c.p." The amount of light entering the eye ranged for the five filters from "99.2–2225.8 c.p." It is presumed that the intention here again was to make the specification in terms of the unit of flux (the lumen), or the units of illumination (the foot-candle, meter-candle, etc.). As it stands the specification is not intelligible. Sheppard found that he was able to get complete adaptation for these higher intensities as well as for the lower ones used previously. He says, "After a long fixation, beyond the point where adaptation was complete, we were able even to raise the comparison-light somewhat higher than the standard, and still had complete adaptation in the fovea." For red the average time required to produce complete adaptation for four observers was 105.3 sec.; for yellow, 166.8 sec.; for blue-green, 120 sec.; for blue, 181.3 sec.; and for violet, 197.0 sec.

Troland (16) in 1921 made a somewhat cursory study of adaptation in which pigment papers were used as stimuli. The papers were illuminated by afternoon sunlight and were viewed at such a distance that the dimensions of the field formed were 60° in the horizontal and 50° in the vertical. Results are given in terms of subjective estimates only, *i.e.*, no attempt was made to measure the effect of adaptation. Prolonged stimulation with strongly illuminated pigments (intensity not specified) did not, he claimed, produce a total absence of the chromatic sensation. With a still higher intensity of illumination of his papers, total adaptation occurred only for yellow and green, and for these colors the effect was not permanent. The greatest change, he says, took place in the first minute. After this the changes were scarcely perceptible. Troland believes that temporary periods of total adaptation are closely associated with pupillary contractions. His conclusions, however, seem primarily to have a theoretical rather than an experimental foundation.

B. Changes in Hue

Whether changes in the hue of color sensations result from the prolonged stimulation of the eye by colored lights has been investigated by Exner, Hess, Voeste and Sheppard. There seem

to be two *a priori* possibilities for the expectation of such changes. (1) Some selective change to wave-length with time of exposure in the chromatic response itself, perhaps a change in the proportionate intensity or in the range of the component responses. Such a change would obviously presuppose a lack of simplicity in the physiological basis of the response to the spectrum stimulus. And (2) a direct action of the achromatic upon the chromatic component of the excitation. The achromatic component, it scarcely need be noted, undergoes a marked change as a result of adaptation. This latter factor, which is effective particularly in the case of yellow and blue, has not been recognized in previous publications on adaptation. In fact the methods used by the earlier investigators have been, for the greater part, such as to preclude or obscure the detection of the effect of this factor. The demonstration that it is a factor was worked out in detail in 1914 by Ferree and Bills but the results of their investigations have not as yet been published.

In making his study of the effect of adaptation on the hue of color Exner,(17) 1868, used the following method. A spectrum was projected on a screen containing two slits, through which the light passed to the eye of the observer behind the screen. By shifting the slits the various colors could be obtained. Two slits were used in order that the effect of adaptation might be observed either on the color used as stimulus or upon another color transmitted by the second slit. At the end of the period of stimulation the hue of the color affected by adaptation was compared with the hue of the same color, not affected by adaptation, as a standard. This standard field was obtained in a very simple way. During the course of the adaptation one of the slits was viewed with the eye at a given distance from the screen.*

* It would seem impossible that the effect of a colored surface could have been given by these slits unless they were covered by some diffusing medium, *e.g.*, ground glass or opal glass. Without this it would seem that the eye would look through the slit at whatever parts of the apparatus were behind the slit. However, no mention is made by Exner of the use of any auxiliary optical device to give the effect of a colored surface. No auxiliary lens for example was used to focus the light on the eye, nor was the eye placed at the focal point of the objective lens of the spectroscope.

At the close of this period the eye was brought closer to the screen. This increased the size of the image of the slit on the retina in proportion as the square of the distance of the two positions of the eye from the screen and decreased the projected size of the previous image, carried over as after-image, in the same proportion. Viewed in this relation the central portion of the colored field represented the color as seen by a fatigued area of the retina and surrounding it an area which had not been fatigued by the previous stimulation. Depending upon the choice of slit used as projection field, the effect of adaptation could thus be obtained either on the color employed as stimulus or upon the color transmitted by the other slit.

A factor apparently not taken into account by Exner, is the effect of the brightness of the preëxposure on the hue of the color that is sensed in the standard field. The object of the use of the standard field was to duplicate, if possible, at the close of the adaptation period, the sensation which was aroused by the colored light at the beginning of this period in order to be able to make a direct comparison between this sensation and that experienced by the fatigued eye. A moment's consideration, however, is sufficient to show that this could not have been accomplished in Exner's experiments. For example, during all of the adaptation period the surface immediately surrounding the slit served as a preëxposure for the standard field. That is, when the eye was moved to the nearer position, the enlarged image so produced, covered an area on the retina which previously had received its stimulation from the field surrounding the slit. The effect of a preëxposure differing in brightness from the color is to give an after-image which mixes with the color sensation and changes both its saturation and hue. If this preëxposure is lighter than the color it adds by after-image a certain amount of black to the succeeding color impression; if it is darker it adds a certain amount of white; and if it is of the same brightness as the color, the effect on the brightness component of the succeeding color sensation is the same or approximately the same as if the eye had been adapting to the color. The effect of fusing white or black with a color is twofold. (1) There is a quantitative effect

due to the inhibitive action of the achromatic upon the chromatic component of the excitation. In general, in the central retina, white inhibits the colors most, the grays in order from light to dark next, and black the least. Also the amount of the inhibitive action varies with the different colors and the state of adaptation of the eye. And (2) there is also a qualitative effect. The hue of certain colors is changed by the action of the chromatic excitation. This change is greatest when the stimuli are yellow and blue. For example, yellow when mixed with black gives a greenish yellow which with the right proportion of components may become an olive green; and blue when mixed with white or a light gray, gives a sensation of reddish blue.

Indeed there seems no way in which a standard field can be used with sureness of principle for the detection of changes in hue resulting from adaptation. Even if it were made of a gray of the brightness of the color the corresponding area of the retina would, as we have already stated, have undergone the same or approximately the same brightness adaptation as the area stimulated by the color, therefore the effect of that component of the adaptation on the change of hue would be lost in making the comparison because it is present equally for both fields. The advantage in general of the use of a standard field on the sensitivity and precision of the judgment, it will be understood, is not called into question here. The difficulty lies in the inability to get a standard field in an adaptation experiment, which does not lead to a false result. In our own observations of changes in hue, for example, we have regarded it as safer to trust to a less sensitive method of making the judgment and employ an observer especially trained to note small color changes as they occur in the course of adaptation.

Our observations on the change in hue and in brightness are given in the appended table, Table II. They are given here instead of in the section on results because they have not been considered sufficiently important and extensive to constitute a separate chapter in the section on results. The observations were made on red (670 mμ), yellow (579 mμ), green (515 mμ) and blue (466 mμ).

TABLE II

Spectrum color	Changes in hue and brightness	Length of time in seconds before a change is noticed for the three photometric intensities 12.5 m.c.	25 m.c.	40 m.c.
Light Adaptation				
Red	Yellows	10 sec.	7 sec.	3 sec.
Red	Darkens	3 "	6 "	10 "
Yellow	Darkens	1 "	4 "	9 "
Green	Yellows	15 "	20 "	25 "
Green	Darkens	2 "	7 "	10 "
Blue	Goes violet	23 "	31 "	48 "
Blue	Lightens	3 "	5 "	8 "
Dark Adaptation				
Red	Yellows	17 sec.	14 sec.	11 sec.
Red	Darkens	11 "	5 "	2 "
Yellow	Darkens	14 "	12 "	8 "
Green	Blues	17 "	13 "	7 "
Green	Darkens	13 "	10 "	7 "
Blue	Goes violet	45 "	70 "	121 "
Blue	Darkens	8 "	4 "	1 "

Hess (18, 19) and Voeste (20) also used two fields in studying the hue changes which occur as the result of adaptation. One of these served as a stimulus field, the other as a comparison field. In the earlier work of Hess the comparison field was employed in the usual way as a standard field to render the judgment as to change of hue easier to make; in his later work and in the work of Voeste, it served as a type of measuring field for the specification of the hue obtained as the result of adaptation. In the first study, two separate fields, side by side, furnished by two spectroscopes, were viewed separately through a telescope by turning it to the right or to the left. One field was outlined by a square diaphragm, the other by a round one. A portion of the retina was fatigued by fixating a point in the circular field at the end of its horizontal diameter, for the desired length of time; then the telescope was turned to the square field and its center as determined by the intersection of cross hairs was fixated. Thus a part of the light from this field fell upon an area of the retina which had been fatigued previously by colored light and a part on an area which had not been fatigued by colored light, but whose powers of response had been modified by the action of its preëxposure field, the brightness of which was not stated. The judgment of change of hue was in terms of the difference between two

fields neither one of which represented the hue of the color as seen by the fresh eye. In his later studies, at the suggestion of Hering, he revised his apparatus and procedure in order that he might designate the change of hue in terms of wave-length. The revision, however, in no way solved the problem presented by the effect of preëxposure in an adaptation experiment. One of his spectroscopes was now provided with two adjustable slits. The stimulus light passed through one of these; the reacting light through the other. The other spectroscope had but one slit and this was set to match, as nearly as could be, the sensation aroused by the reacting light on the color-adapted retina. The telescope in this case was kept in a fixed position and adjusted so that the left half of the field could be illuminated interchangeably by the fatiguing or the reacting light and the right half of the field was illuminated by the comparison or measuring light. The procedure was as follows. The observer fixated a point between the two fields, and the stimulus light was exposed. Adaptation periods of 10, 35, 50, 70, 75, and 180 seconds were used. At the end of these periods the stimulus light was shut off and the reacting and comparison lights presented simultaneously. The position of the slit illuminating the comparison field was adjusted in successive trials to give the closest possible match with the reacting field. With the exception of three lights, namely: yellow (574.5 mμ), blue-green (495–497 mμ) and blue (471 mμ), the hue of all of the lights used shifted towards yellow or blue as the result of adaptation. It was also found that as the length of the period of adaptation was increased, the amount of change in hue was increased.

Voeste (20) also attempted to give a wave-length specification of the change in hue. The periods of adaptation used by him were short, 10–15 seconds. The apparatus employed was a modified Helmholtz color-mixer. Half of the field of this instrument was illuminated by the stimulus light, the other half by the comparison light. The point of fixation was at the center of the field. The light in the comparison field was varied in successive trials until the two fields were brought as nearly as possible to the same hue at the end of the period of adaptation. He found

that the hue of all of the colors between red (660 mμ) and yellow (579 mμ) shifted towards that of the shorter wave-lengths; from yellow-green (560 mμ) to green (500 mμ) and from 460 mμ to the end of the spectrum, the change in hue was towards that of the longer wave-lengths. Blue in the region 490 mμ–460 mμ became, he said, a better blue. A change of intensity of light did not alter the direction of the shift but an increase of intensity changed, in general, the amount of the shift. However, a yellow-green (560 mμ) proved an exception to this. Neither an increase of intensity nor of length of period of adaptation within the limits employed, produced for it a change in the amount of the shift in hue.

Sheppard (21) studied changes of hue for pigment, spectrum and filtered colors. As the result of general adaptation to pigment papers illuminated by sunlight, sensations of red, orange, green and yellow-green were reported by his observers to shift in hue towards yellow, while violet and carmine shifted towards blue. No change in hue was reported for yellow and blue. Very little if any change was reported for any of the colors when the smaller pigment stimuli, rated by him as foveal in size, were used. These stimuli were illuminated by artificial light. Spectrum red changed first to orange and then to yellow. Violet became less red. Spectrum yellow, green and blue of the wave-lengths used by him remained unchanged in hue. When filtered colors were used to fatigue the eye, results similar to those for spectrum colors were obtained.

C. Changes in Brightness

Changes in brightness as the result of adaptation have been studied by Schön. Schön's (22) interest was not directly in adaptation. Prior to the time of his publication, 1874, the sensitivity of the nonfatigued eye to the different parts of the spectrum had been determined frequently. Little agreement had been found in the results obtained by the different experimenters. Schön thought it probable that this lack of agreement in results was due to the fact that the intensity of the source of light used was different in the different investigations. If this were true, the lack

of conformity in the results seemed to him to indicate a fallacy in the Weber-Fechner law, namely that the eye is selective in its response to intensity. For the purpose of testing this point, he performed a series of experiments in which he determined the

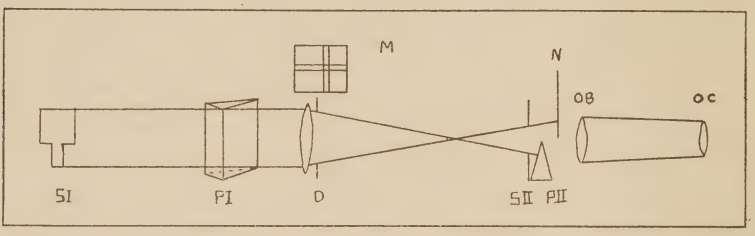

Fig. 2. Schön's Apparatus

SI, Erster Spalt.
SII, Zweiter Spalt.
PI, Erstes Prisma.
PII, Zweites Prisma.
D, Diaphragma mit M, den beiden Bildern davon und dem Fadenkreuz.
N, Schirm zum Abblenden.
OB, Objective. OC, Ocular.

loss or difference in brightness sensitivity of the eye to spectrum lights after fatiguing the eye to these lights. It is not easy to understand how such experiments could throw any light on the point in question. The eye when functioning at a lower level of response, due to fatigue, could scarcely be assumed to have the same characteristics as when functioning at this level due to a decreased intensity of stimulus.

Schön's work is interesting, however, from the standpoint of method. His work alone, of the previous investigators, contains the germ of the quantitative idea of the study of adaptation.

A schematic drawing of Schön's apparatus is shown in Fig. 2. To obtain the spectrum lights, a crude form of spectroscope was used consisting of a slit, a prism and an objective lens. The slit S_1 was so constructed that the upper and lower halves were separately adjustable for the independent control of the upper and lower halves of the beam of light. The light from the slit passed without collimation through the prism P_1, and the objective lens to a screen in which was a slit S_2 for sepa-

rating out the wave-lengths. In front of the lens was a diaphragm D, rectangular in shape. This diaphragm served to outline or define the stimulus field. That is, the light from the slit S_2 passed to the eye through a telescope, of which Ob was the objective lens and Oc the eye piece. When this telescope was focussed for the diaphragm, the opening was seen to be filled with light from that part of the spectrum for which the slit S_2 was adjusted. Between the lens Ob and the slit S_2 was placed a 1.5 degree prism, base down, in such a position that the apex extended to the center of the beam. The effect of this prism in conjunction with the objective lens of the telescope was to form two contiguous images of the diaphragm D, one above the other. These were seen by the eye as two contiguous rectangular fields of the same size and color. One of these served as the stimulus field and the other roughly as a measuring field. Cross hairs, one member of which coincided with the boundary between the two fields, served as a control for fixation. Either of the two rectangular fields could, at the will of the experimenter, be excluded from view by the screen N, also placed in front of the objective lens.

The procedure in making the determinations was as follows. The slits controlling the illumination of the two fields were made equal in breadth. One of the fields was excluded from view by the screen N and the eye fatigued to the other field for a given length of time. Immediately at the end of this time the screen was withdrawn and a comparison made between the stimulus field and the measuring field. If they were not judged equal in brightness, the slit controlling the illumination of the measuring field was readjusted and the series continued until the two fields were brought to equality. Three intensities of light were used, the intensities given by a breadth of slit of 6 mm., 9.5 mm., and 10 mm. No other specification of intensity was given. The intervals of exposure chosen were 3, 5, 10 and 15 seconds. The decrease in the sensation of brightness at the end of these intervals was expressed as a ratio of the width of the slit which controlled the brightness of the measuring field to that which controlled the

brightness of the stimulus field. These ratios are given in the appended table under the heading " Spectrum colors."

TABLE III

Results of Schön's Experiment

Fatigue period in seconds	Fatiguing intensity in terms of slit width	Spectrum colors		
		Green	Red	Blue
5	6.0 mm.	0.50	0.46	0.35
10	"	0.46	0.50	0.33
15	"	0.35	0.50	0.19
5	9.5 mm.	0.37	0.60	0.59
10	"	0.31	0.47	0.37
15	"	0.30	0.43	0.31
3	6.0 mm.	0.59	0.66	0.50
5	"	0.52	0.59	0.37
10	"	0.43	0.59	0.37
15	"	0.37	0.50	0.33
5	10.0 mm.	0.45	0.57	0.45
10	"	0.45	0.56	0.41
15	"	0.41	0.51	0.40

Schön concludes from these results: (a) that after 5 seconds exposure to spectrum red, green or blue, half of the brightness of the color is lost; (b) that further decrease in brightness takes place gradually; and (c) that the effect is least for red and greatest for blue.

Of all the previous investigations, Schön's is without doubt the most scientific. He has shown too the best grasp of the methodologic problem presented. With regard to his work, however, and the treatment of the problem, the following points may be noted. (1) The device for obtaining spectrum light was crude and must have given light of a low degree of purity. A spectroscope without some collimating device could hardly be relied upon to give the regularity of dispersion needed for a satisfactory resolving power. Also there seems to have been no provision whatever in the spectroscopic system to guard against scattered light. This deficiency must have added greatly to the impurity of light obtained. (2) He assumed that the intensities in the upper and lower halves of his beam of light and therefore in his stimulus and measuring fields, were the same. This assumption in turn served as a basis for two further assumptions, namely that the sensations aroused by the stimulus and measuring fields were of the same brightness and that the ratios of the slit width

used for the measuring field to the constant slit width for the stimulus field, gave the correct relative values of the intensities of light in the measuring field. Three flaws in these assumptions may be pointed out. (a) To assume complete homogeneity in the upper and lower halves of a beam of light, obtained as the one in question was obtained, could not be justified; besides, the intensity of the lower half of the beam was reduced by the absorption of the prism P_2. (b) Even if the two fields were equally illuminated, it could not be assumed that the contiguous areas of the retina would give sensations of equal brightness. The deviations from equality would be a function not only of the parts of the retina stimulated, but also of the wave-length and intensity of light used. (c) The error involved in the third assumption, namely that the ratios of the slit widths used for the measuring field to the constant slit width for the stimulus field gave the correct relative values of the intensities of light in the measuring field, is too obvious from what has gone before to need comment; moreover, the procedure was entirely unnecessary. (3) One of his conclusions is that the sensation loses half of its brightness after the eye has been exposed to light for a period of 5 seconds. This conclusion is apparently based on the fact that at the end of 5 seconds, the light had been reduced one-half, within the limits of error of his method of making the determination. Such a conclusion ignores the selectiveness of the eye's response to intensity of light and its change with change of wave-length. It would be bad enough to assume this simplicity in the psychophysical relation in the non-fatigued eye. What the law of relation is or even any of its characteristics is entirely unknown for an eye whose sensitivity has been changed by adaptation. (4) Schön was obviously attempting to trace the loss of sensitivity during the course of adaptation by some form of the method of equivalents although the requirements for a quantitative use of this method do not seem to have been fully worked out by him. What should have been done in the use of this method was first to bring the stimulus field and the measuring field to the same subjective brightness with the eye unfatigued. The amount of light in each field should then have been measured

in energy terms and the sensitivities of the corresponding areas of the retina rated as the reciprocals of these energy values. The eye then should have been fatigued for the first of the periods used in his adaptation series, at the end of which time the brightness of the measuring field should again have been made to match that of the stimulus field and the sensitivity again have been rated as the reciprocals of the light energies in the two fields. From the percentages expressing the sensitivity of the stimulus area of the retina to that of the measuring area before and after adaptation, a numerical value could have been obtained for the loss of sensitivity as the result of adaptation, assuming of course that the sensitivity of the measuring area had been maintained constant. For this no special precautions were exercised, at least none were described. This procedure repeated for the different intervals used in the series would have given a number of percentages from which the progressive loss of sensitivity as the result of adaptation could have been computed. Schön, however, did not do this. No value was determined expressing the relation of the initial sensitivity in his stimulus area to that of the measuring area. The first matching of the responses and therefore the first opportunity to compare the sensitivity of the stimulus area with that of the measuring area, came at the end of his first adaptation period, the second point in his series instead of the first. Had he taken the slit width controlling the light on the measuring field at this point in the series as his base with which to compare all subsequent slit widths, the procedure could have been made quantitative for the remainder of the series. Instead of this, he compared each slit width for the measuring field with the constant slit width for the stimulus field. He did not even make the comparison with the initial slit width for the measuring field. (5) There was no specification of the amount of light used. It is very important that there should have been such a specification for the rate of loss of sensitivity with adaptation changes very greatly with the intensity of light used and the effect of intensity is different for the different wave-lengths. (6) He compares the rate of adaptation for the different wave-lengths of light used. It should be noted that this comparison could be made quantitatively

only in case the same composition and intensity of light were used throughout in the measuring field. That is, if a comparison of sensitivities is to be made for the different wave-lengths and intensities, the area of the retina which is used to measure the various sensitivities must itself have the same sensitivity throughout; in other words, it must be acted upon by light of the same composition and intensity throughout. This would require, in case the lights in the measuring and stimulus fields differed in composition, a judgment of brightness equality in the presence of hue difference, a task no more difficult than is ordinarily involved in heterochromatic photometry. (7) As stated in the introduction, the use of the method of equivalents to rate sensitivities presupposes that a constant state of sensitivity be maintained in the measuring area of the retina. That this can be accomplished under such unusual conditions as are imposed in an adaptation series is highly improbable, as has already been indicated and discussed. For example, the achromatic sensitivity of the measuring area of the retina from which the light is shut off during the fatiguing of the stimulus area is continually changing and by different amounts for different lengths of adaptation. That is, while the area whose sensitivity is to be measured is continually losing sensitivity, the area by means of which the sensitivity is to be measured is continually gaining in sensitivity. In short, the choice of the method of equivalents is, we believe, an unfortunate one for rating loss of sensitivity by adaptation.

Summary of History.

The first experiment with reference to the change in the response of the retina to a chromatic stimulus as the result of fatigue to that stimulus was reported by Plateau in 1834. Experimenters who have investigated the effects of fatigue to color, general or local, may be classified as follows: (a) those whose purpose it was to study partial or total loss of saturation; (b) those whose interest was directed to changes in hue; and (c) one who investigated changes in brightness. In the first group may be included Plateau, Bokowa, Aubert, Burch, Beck, Porter, Edridge-Green, Brückner, Sheppard, Troland, and Ssamujlow;

in the second, Exner, Hess, Voeste, and Sheppard. The method of working and the stimuli used vary widely and only a few general conclusions may be drawn. No work has been done that can be called quantitative. In general the problems have been only vaguely formulated and in many cases very little control has been exercised over the conditions under which the work was done. The following points have been claimed: the length of adaptation required to produce a given partial or total loss of saturation varies with the hue (Aubert, Burch, Ssamujlow), with the saturation (Sheppard), and with the brightness (Sheppard and Troland). During adaptation most colors, pigment or spectrum, change in hue towards yellow or blue. However, there are a few which are reported to be stable in hue. The following table shows the regions where no change is noticed:

TABLE IV

Regions in the spectrum in which previous investigators report no change in hue as the result of adaptation.

	Unchanged Regions			
Investigators	Red	Yellow	Green	Blue
Exner	From the extreme end to between the C and D lines		Between lines E and B	Near line G
Voeste		560		
Hess		574.5	495–497	471
Sheppard		545–575	495–525	440–470

Schön reports that for red, green and blue there is a rapid decrease in the brightness of the stimulus as the result of adaptation.

Aubert reports also an effect of the brightness of the surrounding field and size of visual angle upon the rate of loss of saturation and Beck and Burch an effect of achromatic adaptation both on the hue and saturation of the color.

III. EXPERIMENTAL

In order to make a study of the progressive loss of sensitivity of the eye under the conditions outlined in our introductory chapter, the following provisions were necessary: (1) an optics room which could be used both as a light and a dark room; (2) provisions for a precise control and reproduction of the intensity of illumination of the light room; (3) apparatus for presenting to the eye the desired spectrum lights, free from impurities; (4) apparatus for measuring the energy of the light waves used as stimuli; (5) devices for equalizing the stimuli as to photometric value, energy value, and saturation; and (6) apparatus for reducing the stimulus to the threshold value immediately at the cessation of the fatigue period. A description of the optics room and the apparatus needed to satisfy these requirements, the method of procedure for making the energy measurements, and the method of determining the loss of sensitivity, are given below. The arrangement of the apparatus and the path of the beam of light from the source to the eye are shown in Figure 3. Photographs of the apparatus are given in Figures 4 and 5. Far the greater part of spectroscope and radiometric apparatus employed have been used previously in the Bryn Mawr laboratory and have already been described in considerable detail.

A. The Optics Room

One of the purposes of the investigation was a comparison of the results for a light-adapted eye with those obtained with a dark-adapted eye. The apparatus was set up, therefore, in a light room which could be converted into a fairly satisfactory dark room by means of a light-proof curtain. The conditions for complete dark adaptation were further provided for by enclosing the source of light and the spectroscope together with its auxiliary apparatus for presenting the light to the eye, in a light-proof compartment, and by hooding the head of the observer.

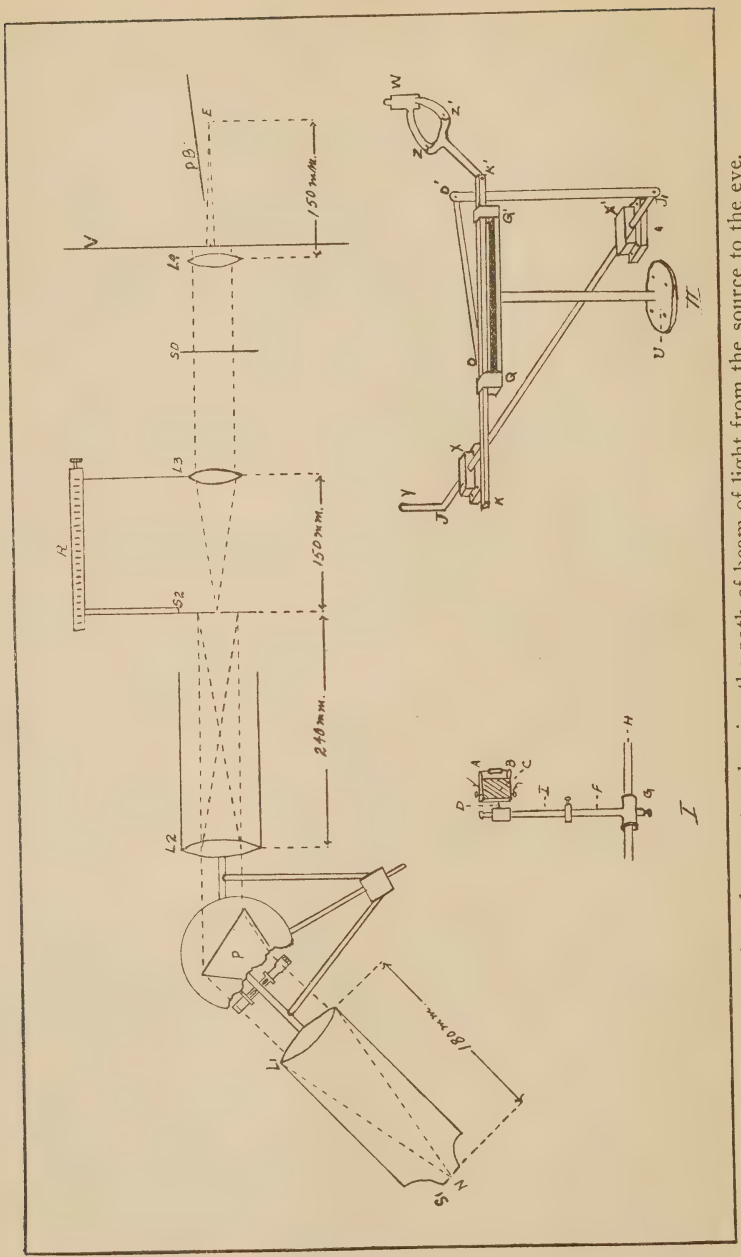

FIG. 3. Drawing of apparatus showing the path of beam of light from the source to the eye.

1. *The Light Room.*

The light illuminating the room came from a skylight covering almost the entire ceiling. Beneath this skylight were swung large sashes of ground glass. These sashes served to diffuse the light

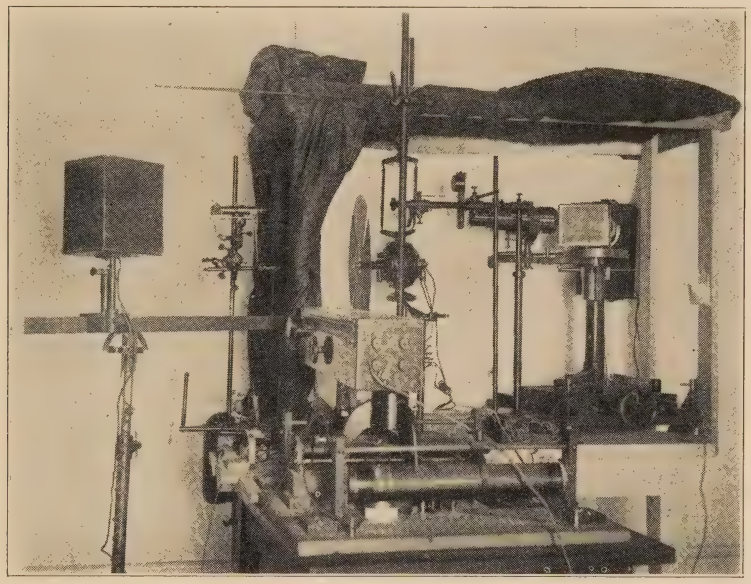

FIG. 4. Showing the apparatus assembled for work.

and to give an even illumination of the room. In order to keep the daylight illumination constant, a means had to be provided for making small changes in illumination and for measuring the amounts obtained. The following provisions were made for changing the illumination: Gross changes were made by means of a light-proof curtain, covering the entire ceiling. This curtain moved on wire supports to prevent sagging and its edges were enclosed to a depth of one foot, in a light-proof boxing extending around the entire room. Fine changes were made by means of thin white curtains also supported by wire guides. One set of these extended lengthwise of the room, the other across the room. The illumination was measured by means of a Sharp-Millar illuminometer, placed as close as possible to the stimulus field at the

point of work. This illuminometer is shown in position in Fig. 4, with the exception that it had been lowered in taking the picture in order to prevent the obscuring of important parts of the apparatus. The component of illumination received upon its

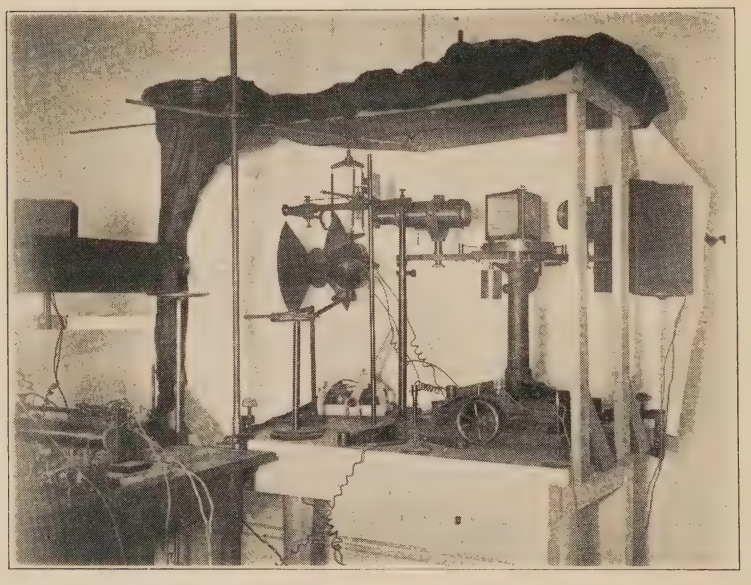

FIG. 5. Second view of apparatus.

test plate was the same as that which fell upon the stimulus opening and its surrounding field. A glance at the field of the instrument was thus sufficient at any time to tell whether this component had changed from that selected for work. The photometric match between the daylight and the light from the lamp of the illuminometer was rendered easy to make by the insertion of appropriate colored filters of known coefficient of transmission. The spectroscope and the optical system were shielded from the light of the room as a source of impurity by the light-proof compartment in which they were enclosed. This was, of course, a very important reason for enclosing the path of the beam from its source to the eye. The illumination of the room was kept constant for the work under light adaptation at 214 foot-candles, horizontal component, and 221 foot-candles, vertical component.

2. The Dark Room.

In the work under dark adaptation, the following means were used to exclude extraneous light from the eye of the observer: (1) The light-proof curtain was drawn completely across the room. The inner surfaces of the boxing in which all four edges of the curtain were encased to a depth of one foot were painted a mat black. (2) The Nernst filament which served as source for the spectrum light was enclosed in a specially ventilated, light-tight metal housing. This housing had a circular opening in one end into which the collimator tube of the spectroscope was inserted well beyond the collimator slit. This opening fitted tightly about the collimator tube and its edges rested against a shoulder on the tube, which helped further to prevent leakage of light from the housing into the room. The housing was painted a mat black both inside and outside. A door at one side provided a means of entrance to the housing through which the position of the Nernst filament in front of the collimator slit and the width of the slit could be adjusted. The housing was supported on a metal stand clamped to the table on which the spectroscope stood. (3) A wooden frame built about the spectroscope and the auxiliary optical apparatus, used for presenting the light to the eye, was covered with three layers of heavy black cloth. At one end of the enclosure was placed the screen containing a small circular opening through which passed the beam of light used to stimulate the eye of the observer. As a precaution against the scattering of light within this enclosure and the resulting impurities in the spectrum beam, every surface within the enclosure which could be so treated without interfering with the optical properties of the system was painted a mat black. (4) A large hood or curtain of black cloth was fastened at the screen end of the dark cabinet just described. This curtain enclosed the head and shoulders of the observer and completely shielded the eye from any residual stray light. It was removed in the work under light adaptation. The other enclosures were retained as a precaution against the entrance of scattered light into the spectrum beam. Figures 4 and 5 show the covering removed from one side of the dark cabinet. For photographic purposes the interior was lined with white cloth.

B. The Apparatus

A schematic representation of the apparatus and the beam of light is shown in Figure 3. The light from the Nernst filament N passes through the collimator slit S_1, the collimator lens L_1, the prism P, and is focussed by the objective lens L_2 in the plane of the objective slit S_2. The monochromatic light from S_2 is collimated by the lens L_3 and focussed on the pupil of the eye, E, by the lens L_4. Between L_3 and L_4 is inserted, when desired, the sectored disc SD, which is used to reduce the stimulus light to threshold intensity. The sectored disc, already rotating and adjusted as to width of open sector, is made to cut the light beam at the end of the fatigue period by a device which will be described later. Photographs of the apparatus are shown in Figures 4 and 5.

1. *The Source of Light.*

A seasoned Nernst filament operated at 0.6 ampere was used as the source of light. For this purpose it has the following advantages: (a) When properly seasoned it gives a light very constant both in intensity and composition; (b) its flux of light is sufficiently great to permit of a direct measurement of the energy of the wave-lengths of the different parts of the spectrum and to provide the high intensities needed for a thorough study of the eye's powers of response; and (c) its shape is well adapted for use with the slit of the spectroscope, *i.e.*, the shape is such as to make it possible to utilize for the illumination of the face of the prism a relatively large part of the light emitted. When in use the filament is placed as close as possible to the slit and directly in front of it. In doing this care must be taken that the position of the filament in relation to the slit is always the same, for the light which enters the slit should always come from the same part of the filament else changes both in its composition and intensity may occur. Two difficulties are encountered here: (a) The Nernst material must be heated before it will conduct the electric current. This requires that the filament be moved from its position in front of the slit and replaced prior to each period of work. (b) The terminal wires, which are platinum and very pliable, give

little stability of position to the filament. To overcome these difficulties a special mounting has been devised which provided for the removal and precise resetting of the filament and gives the rigidity of support needed to prevent sagging or other displacement. This mounting is shown at I in Figure 3.

The terminal wires of the filament N are attached to the two metal arms A and B. These wires pass through grooves in the ends of A and B and are fastened down under tension by screws farther back. So supported and tensed, the filament is held firmly in position without risk of sagging or other interference with its alignment. Back of the point of attachment of the terminal wires and in circuit with them are binding posts for connection with the line. A and B are fastened above and below a block of asbestos, C, which provided both heat and electric insulation for the filament and its supports. C is fastened on the rod I by pin D. This permits of a slight rotary movement which is frequently needed in making a perfect alignment with the slit. The rod I telescopes into tube F, which is fitted with a collar and set screw, and F is in turn fastened by a collar and set screw, G, to a rod extending out from the collimator arm. By means of these various mountings the filament may be moved back and forth, right and left, up and down, and in addition be slightly rotated about the pin D. As already stated, the filament with its mountings is enclosed in a specially ventilated light-proof housing provided with a door at one side. This filament is connected in series with a Weston ammeter graduated to 0.02 ampere; a ballast which both reduces the current and compensates for changes in the resistance of the Nernst material with change in temperature; and two adjustable rheostats, one coarse, to cut down the current approximately to the desired value, the other fine, to correct for fluctuations in the line.

2. The Spectroscope.

The essential parts of the spectroscope are shown in Figure 3. S_1 is the collimating slit; L_1 the objective lens; and S_2 the objective slit. The spectroscope was designed to give high intensities of light. For this reason large lenses, a large prism, and a long

collimating slit are needed. The length of the collimator slit is 12 mm. The breadth was regulated by a micrometer screw with a head graduated to thousands of an inch. Both lenses were Zeiss triple achromats, 60 mm. in diameter. The focal length of the collimating lens was 180 mm.; of the objective lens, 240 mm. The prism was 100 mm. high. The length of the refracting base was 115 mm. and the refracting angle was 60°. Because of its large size, a liquid (CS_2) prism was used. In order to guard against changes in the refracting index, care was exercised to keep the CS_2 free from impurities and to maintain the temperature of the room as nearly constant as possible. The objective slit was of fixed breadth, 0.446 mm., and adjustable in length in half millimeter steps. Space will not be taken here for a description of the device by which these adjustments were made. In brief, it consists of two knife-edged jaws, moving in the vertical, operated by means of a ratchet and spring. The length of aperture attainable ranged from 0–12 mm. The length used for the work on the eye in these experiments was 2.027 mm.; for the energy measurements it was increased to 11.6517 mm., and the appropriate correction factor was applied. The shorter length was used in presenting the light to the eye in order that its focussed image might fall within the pupil and thus render the amount of light entering the eye independent of changes in the size of the pupil. To make possible a minimum deviation setting for all wave-lengths falling on the objective slit, the spectroscope was provided with a minimum deviation attachment. For a detailed description and explanation of this attachment and other features designed to meet the wide range of special needs of a spectroscope which is to be used in the study of the responses of the eye, the reader is referred to an article published from this laboratory in 1916 (Journ. Exper. Psychol., 1916, I, pp. 247–283).

In order to make quantitative determinations of the sensitivity of the eye, it is necessary that lights of a high degree of purity be used. The presence of alien wave-lengths in the stimulus light affects the results of the determination in two ways: (1) through physiological inhibition and interactions it decreases the amount of the color response; and (2) it increases the energy value of

the stimulus. From both of these causes the numerical value given to the expression for sensitivity is decreased. For the purpose of securing the needed degree of purity, the following precautions were used: (a) The spectroscope was set to give minimum deviation for the D line and the changes of wave-length were produced by the minimum deviation attachment just referred to. (b) Internal reflections were eliminated as far as possible by blackening every surface within the spectroscope that could be blackened without interfering with its optical functions. (c) The beam was protected against the entrance of extraneous light by housing the spectroscope and the auxiliary optical system in the light-proof enclosure previously described. And (d) the residual impurities found in the spectrum, produced by every lens-prism spectroscope, were absorbed by thin gelatines selected so as to cut out the alien wave-lengths and reduce the useful light as little as possible. These gelatines were held in place over the objective slit by short metal clips fastened to the jaws of the objective slit. In every case the energy measurements were made of the stimulus light after it had passed through these filters.

3. *The Auxiliary Optical System.*

As already noted, the plan of work included studies both under light and dark adaptation. One of the problems in the use of a spectroscope in the study of the responses of the eye under light adaptation is to get a method of presenting the light to the eye that will give the effect of a colored field and at the same time prevent the admixture of the light from the room. For example, the following methods have been used in dark-room work to give the effect of a colored surface or field to image on the retina: (a) The light may be allowed to fall on a diffusely reflecting surface; or (b) it may fall on a diffusely transmitting surface. Obviously neither of these two methods could be used in light-room work without a prohibitive amount of admixture of white light with the spectrum beam. They are, in addition, open to the following objections: (1) Both require that the surfaces used be absolutely nonselective to wave-length. (2) Both are unduly wasteful of light. Not only is the amount of light reflected or transmitted,

reduced by absorption which is usually comparatively great in case of a diffusely transmitting medium, but only an extremely small percentage of the light which leaves the surface enters the pupil of the eye. (3) The energy value of the light entering the eye cannot be measured directly; it can only be computed roughly. (4) The amount of light entering the eye cannot be made independent of size of pupil without the use of an artificial pupil. All of these objections are very simply eliminated by the optical system which has been devised as an auxiliary to the spectroscope described. That is, there is no admixture of extraneous light with the spectrum beam; all of the light energy from the objective slit of the spectroscope is concentrated into the beam which enters the eye; the energy measurements may be made directly at three places, the objective slit, the opening in the screen used to control the size of the field imaged upon the retina, and the eye; and the amount of light entering the eye is made entirely independent of the pupillary reaction without the annoyance and the risk of optical error which may attend the use of an artificial pupil. The principle employed in this system is the same as that used when the eye is placed at the objective slit of the spectroscope. That is, when the eye is placed at the principal focus of a convex lens receiving parallel rays of light, the lens appears to fill uniformly with light. The principle has been modified, however, to give a better control of conditions and a wider range of serviceability than is attained when the eye is placed at the objective slit of the spectroscope. Instead of placing the eye at the slit, a lens L_3 is placed at its focal length from the slit and the parallel beam thus obtained is focussed on the pupil of the eye by another lens L_4. The latter lens, therefore, is seen uniformly filled with light and the colored field which it presents is diaphragmed down to the desired size by a circular opening in the screen V. Among the advantages gained by this method of obtaining the stimulus field, the following may be noted: (1) So controlled, the amount of light entering the eye may more easily and conveniently be made independent of variations in the size of the pupil than by placing the eye at the objective slit of the spectroscope. (2) The variable effects of brightness of preëxposure and surrounding field may be

eliminated. (3) Ample room is provided for inserting in the path of the beam the apparatus which is needed for reducing the intensity of light or for other purposes which may be required. And (4) so supplemented, the spectroscope may be used in connection with the rotary campimeter (Journ. of Exper. Psychol., 1916, I, pp. 276–283) for the investigation of the sensitivity of any part of the retina, central and peripheral.

Another important feature of the spectroscope employed is its focussing device. That is, in a spectroscope which has an independent slit and an ocular, the objective lens of which is intended to collimate the beam of light, a means must be provided for focussing the instrument for the different wave-lengths of light without altering the distance between the slit and the collimating lens. This has been accomplished by the device shown at R in Figure 3. A carriage made up of two sleeves and a connecting bar is made to travel along a hollow steel tube by a driving screw. Extending out from one of these sleeves, on a rod, is a holder for the collimating lens and from the other is the frame which carries the objective slit. The thread of the driving screw engages only the first of these sleeves; the other sleeve is made to follow because of the connecting bar. To provide for lenses of different focal lengths, the connecting bar is slotted and furnished with a set screw. In adjusting the collimating lens, the driving screw is turned until the distance of the lens from the slit is equal to its focal length. The set screw is then tightened and any further motion of the driving screw serves to move both lens and slit by equal amounts. In focussing the spectroscope for the different wave-lengths, therefore, the slit and the objective lens of the ocular move in constant relation and the collimation of the spectrum beam is not disturbed. This focussing device is mounted on an adjustable tripod stand which is screwed fast to the table.

The dimensions of the image focussed on the eye were 2.0148 mm. x 0.47191 mm. They were determined by photographing the image on a plate mounted in the exact plane of the pupil and measuring the image with a micrometer comparator.

The aperture of the lens was diaphragmed to the size wanted for the stimulus field by a screen V, with a circular opening 13

mm. in diameter, subtending a visual angle of 5° 44′ at the eye. In the work under light adaptation this screen was made of a gray of the brightness of the color in order to eliminate all contrast effect from the surrounding field. The position of the eye at the focal point of the lens L_4 was fixed by having the observer bite a mouth-board in which the impression of his teeth had previously been made and hardened in wax.

4. *Apparatus for Reducing the Intensity of the Stimulus Light.*

As stated in the introduction, it was decided to make the first attempt at a quantitative study of the loss of chromatic sensitivity as the result of adaptation, by determining the threshold at the end of each adaptation period. In making this determination it is necessary that the sensitivity of the eye be determined for the same light to which the eye has become fatigued. This not only requires a means of making finely graded reductions but it also requires some provision for applying them immediately at the end of the adaptation period. The reductions were made by means of finely graded sectored discs rotated by motor which was suspended by three coiled springs from a point above and to one side of the center of the beam of light. By shifting this motor back and forth the desired amount along the arc determined by this suspension, the rotating discs which it carried could be interposed in the path of the beam or removed from it at will. The shifting of the motor was provided for by the apparatus shown at II in Figure 3. This apparatus consists of the following parts: a stirrup the arms of which, ZZ′, are attached to an extension W. which screws into the motor; a rod, KK′, which is attached by a swivel joint to the shank of the stirrup and moves back and forth horizontally in the bearings QQ′; and a right angled arm JJ′O′, which is made to rotate through a quarter turn in its bearings XX′ by the handle Y. As it rotates it moves the rod KK′ back and forth by means of shaft OO′. The shaft OO′ is also provided at either end with a swivel joint. The rod KK′ and its bearings are supported on a stand the base of which, U, is screwed fast to the table. The bearings XX′ for the arm JJ′O′ are also screwed fast to the table. The joint at J′ in the arm JJ′O′ was made rigid

in order that when the handle attached to the arm was rotated, both members of the arm would rotate. The longer member of the arm, JJ′, passed through the front wall of the compartment enclosing the spectroscope and its auxiliary apparatus. The handle Y was within easy reach of the observer when in position for work.

The sectored discs employed were cut from hard sheet aluminum, number 20 B. and S. gauge, 0.9 mm. thick. They gave a range of variation of apertures in finely graded steps from 0°–348.75°. The set consisted of five pairs of two-sector discs and one pair of one-sector discs provided with a counterbalancing weight. In the first pair the breadth of the two open sectors was 90° and the range of variation of total open sector was from 0°–180°; in the second pair the breadth of each of the two sectors was 45° and the range of variation of total aperture was from 180°–270°; in the third pair the breadth of each of the two sectors was 22.5° and the range of aperture was 270°–315°; in the fourth pair the width of each of the two sectors was 11.25° and the range of aperture was 315°–337.5°; and in the fifth pair the breadth of each single sector was 11.25° and the range of aperture was 337.5°–348.75°.

In order to obtain very small apertures or to make small variations of aperture when each open sector was 15° or less, a small single sector furnished with a counterbalancing weight was provided in addition to the five pairs of discs. When this was used to cover one of the open sectors of the pair of discs having 90° sectors, the total aperture could be varied from 0°–15°. This single sector could also be used with any of the other pairs of discs to aid in making smaller variations in the total aperture than could be obtained with that pair of discs alone. That is, as one of the sectors was opened, the other could be closed by any desired amount less than 15° by means of this single sector. For the purpose of making small changes of opening, a micrometer adjustment was provided which could be detached before the discs were rotated. Small values of aperture were read with a high degree of precision by means of a protractor supplied with a Vernier scale reading to minutes of arc.

For timing the adaptation periods, a laboratory clock connected in series with two dry cells, a key, and a telegraph sounder, were used. The pendulum of the clock made contact with a mercury meniscus every second.

5. *The Photometric Apparatus.*

Each of the spectrum lights was photometered against a seasoned 40 watt tungsten lamp operated at 0.34 ampere. This lamp was mounted at such a height on the bar PB, Figure 3, that the center of the filament was in line with the center of the stimulus opening. In order to provide a photometric field, the stimulus opening was surrounded with a white surface, coefficient of reflection 85 per cent. For each series of experiments at the different intensities of light, the lamp was set at the position on the bar which gave the desired intensity of illumination of the photometric field when the appropriate corrections had been made for the coefficient of reflection and the cosine law. The spectrum lights were equated in brightness to this field by changing the width of the collimator slit.

6. *The Radiometric Apparatus.*

The apparatus consisted of a Coblentz linear thermopile; a sensitive Thomson galvanometer, specially constructed for use with this thermopile; and various accessories, including a sensitivity tester for the galvanometer, resistance coils to reduce the throw of current from the thermopile, and a reading telescope and scale. For a detailed description of this apparatus the reader is referred to an article by Ferree and Rand, " Radiometric Apparatus for Use in Physiological and Psychological Optics " (Psychol. Monog., No. 103, pp. 54–65).

C. Method of Working

1. *The Radiometric Measurements.*

For this investigation, the energy measurements were made both at the objective slit and at the eye. In making the measurements at the objective slit the thermopile to be used is placed in

position immediately behind the slit and a blackened aluminum shutter is interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer is tested by means of a special device provided for this purpose in the galvanometer circuit. With regard to this procedure, it scarcely need be pointed out that the current sensitivity of the galvonometer varies with the period of time of the single swing of its needle system. Since it is impossible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a factor determined at each sitting. For a detailed description of the method of determining this factor, see Psychol. Monog., No. 103, pp. 60–65.

The thermopile is next connected with the galvanometer and the light allowed to fall upon the receiving surface until a temperature equilibrium is reached (about three seconds for the thermopile in question). The deflections are read by means of a telescope and scale and the factor is applied to correct the readings to standard sensitivity. The final step in the process of measuring is the calibration of the apparatus, *i.e.*, the energy value of 1 mm. of deflection of the galvanometer at standard sensitivity is determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiation from which is already known, has to be employed. The standard used by us was a carbon lamp specially seasoned and prepared for the purpose by W. W. Coblentz of the radiometric division of the Bureau of Standards. This lamp was placed on a photometer bar two meters from the thermopile and operated at one of the intensities for which the calibration was made,—in this case 0.40 ampere. The thermopile was exposed to its radiation with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection was recorded. From the deflection obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, was computed from the known amount

of energy falling on the surface of the thermopile. Having this factor expressing the radiation sensitivity of the apparatus, the deflections produced by the lights measured were readily converted into energy units. The radiation sensitivity of the thermopile used in this work was computed from the following data: The energy of the radiation per sq. mm. at a distance of two meters from the Standard lamp operated at 0.40 ampere was 90.70×10^{-8} watt. The total energy falling on the thermopile for the area of surface exposed was 471.97×10^{-8} watt. The deflections of the galvanometer corrected to a sensitivity of $i = 1 \times 10^{-10}$ ampere and for the absorption of the glass covering of the thermopile was 733.26 mm. The sensitivity of the instrument was therefore 64.366×10^{-13} watt.

In the present investigation the determination of the energy of light entering the eye is, of course, of primary interest. Because of the small amount of energy represented in the short wave-lengths of the spectrum, it is difficult to measure them with the desired degree of precision at the eye even with a sensitive apparatus. It has been considered advisable, therefore, to measure the red both at the slit and at the eye, and from the results obtained to compute a factor which can be applied to the values at the slit for the other wave-lengths to convert them into values at the eye.

As was stated in the introduction, the observations were made with the stimuli equalized in brightness at 12.5, 25, and 40 meter-

TABLE V*

Showing total energy values at the eye. The values are in terms of watt $\times 10^{-12}$.

A. When the lights were made equal photometrically at 12.5, 25, and 40 m.c.

M.C.	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
12.5	5,531.672	131.496	180.088	1,050.595
25.0	9,761.196	301.633	296.629	2,653.874
40.0	16,674.082	657.152	656.821	4,979.791

B. When lights were made equal in saturation to the saturation of yellow at 25 m.c.

657.270	301.633	4.181	120.164

C. When the lights were made equal in energy to the green at 40 m.c.

656.821	656.821	656.821	656.821

* The energy measurements given in this table were made by Dr. Gertrude Rand.

candles; equalized in saturation to the saturation of yellow at 25 meter-candles; and equalized in energy to the green at 40 meter-candles. The energy values of the stimuli under all of these conditions were determined. The energy values at the eye are given in Table V. A division of these values by .951 will give the energy density at the eye; a division by 132.7, the energy density at the stimulus opening.

2. The Determination of Loss of Sensitivity.

The procedure in making the determinations was as follows: The eye was presensitized to each condition of illumination by a period of adaptation, thirty minutes in the dark room and fifteen minutes in the light room. In the preliminary work these periods of adaptation were found to be sufficiently long to give constancy of result. The observer was seated in front of the apparatus with the eye at the focal point of the lens L_4. To insure steadiness of position, the head was held rigid by means of a mouthpiece coated with wax in which the impressions of the teeth had been previously made and hardened. The other eye was bandaged with a black cloth. As an aid to fixation a black dot was made at the center of the anterior surface of the focussing lens. When this was fixated, the stimulus opening appeared to fill uniformly with light. In making the determinations of the threshold, at the end of the fatigue period the sectored discs, adjusted to an approximate value and already rotating, were made to cut the light beam by means of the device for shifting the motor previously described. A large number of trials was required, of course, to secure the exact value of aperture needed to bring the stimulus to threshold intensity. Between each of these trials, rest periods of several minutes were given. The length of these periods varied with the period of stimulation and with the intensity of light used. Blinking, too, is a source of variable error of no small importance in the determination of adaptation effects. Blinking interferes with adaptation in two ways: by relieving the eye from stimulation and by the direct action of the accompanying movements of the eye. These movements, known as Bell's phenomenon, are downward and inward with the closing of the lid and upward and out-

ward with the opening of the lid (Philos. Transact. of the Royal Soc., 1823, 113, 289). Since blinking cannot be prevented, especially in case of intense light and long periods of stimulation, its frequency has to be regulated or standardized. In the present experiment the observer blinked at the end of every fifth second during the fatiguing period, timing herself by the telegraph sounder previously mentioned. Also, in each case in the light room work, the surrounding field was made equal in brightness to the color, in order to eliminate as far as possible the effect of physiological induction on the chromatic component of the excitation, both for the fresh eye and during the process of fatiguing. The determinations were all made in ascending and descending series.

The time consumed in making the determinations was necessarily very great. Even after the required practice was given for each color under each condition of working, only a small number of points in the curve could be determined at a single sitting. In such a case the question naturally arises, How can one put together in a single curve determinations made on different days and be reasonably sure that the differences represented are due to the process investigated and not to some change in the condition or sensitivity of the eye? The reply is that in cases of this kind, where a number of results taken at different times have to be compared with reference to the effect of a given variable, the same type of precaution has to be applied to the use of the eye as is exercised when a sensitivity tester is used in connection with a galvanometer or other physical instrument whose sensitivity is liable to vary from time to time. That is, on resuming the work at any particular sitting, it had first to be determined whether the curve made at the preceding sitting could be picked up or duplicated at one or more points. When this can be done, one is justified in assuming that the eye has not changed its characteristics of response with reference to the function investigated, and the work may be allowed to continue on that day. If the curve cannot be picked up, the work should not be allowed to continue. As a further precaution, each determination was checked by a number of repetitions. The work of making the determinations

alone, consumed approximately 400 hours. The time required to acquire the desired degree of precision in making the observations and in manipulating the apparatus and controls is not included in this estimate, nor the time consumed in making various measurements, radiometric, photometric, and colorimetric.

As bearing upon the explanation of adaptation, it may be of interest to note some of the phenomena that took place in determining the threshold for the fatigued eye. As the stimulus was made to approach the threshold value in the successive determinations, descending series, the color was seen less and less saturated until the threshold was reached. If the reduction were carried beyond this point, the stimulus was sensed first as gray and then in the after-image color, which grew progressively stronger as the amount of the reduction was increased. In the use of the ascending series, these phenomena occurred in the inverse order. Any movement of the eyes while observing the stimulus field either in the process of fatiguing the eye or in making the threshold determination revealed the after-image in that segment of the projected field which had been moved out of coincidence with the stimulus field; also the part of the stimulus field for which the after-image had been removed appeared to have undiminished saturation. All judgments were based on the appearance of the center of the field where there was little or no effect of the slight eye movements which might take place. The eye recovered its sensitivity as the after-image died away and appeared to have fully recovered when no trace of the after-image was revealed in the surrounding field by an eye-movement. The obvious inference from these phenomena is that the after-image process and the adaptation process are one and the same; the after-image is revealed only when the projection field does not sustain a complimentary relation to the after-image color or, when it does sustain the complementary relation, it is not of sufficient intensity to cancel or inhibit the after-image color.

IV. RESULTS

As stated in the introduction, the results on this study were obtained under three conditions: (1) The lights were made equal photometrically at three intensities: 12.5, 25, and 40 meter-candles. The determinations made under these conditions serve a two-fold purpose: (a) They give us an indication of the importance of brightness as a factor in chromatic adaptation. However, for spectrum lights the effect of brightness and saturation as factors cannot be studied in separation. That is, neither can be varied independently of the other without the introduction of mixed light into the spectrum beam. If mixed light is introduced into the beam of spectrum light, the study is complicated by the presence of a variable purity, a factor of as great importance in the results, perhaps, as either saturation or brightness. And (b) they provide us with knowledge of the comparative rates of adaptation to color under the conditions which prevail in lighting, namely, equal photometric intensities. This latter feature was a very important incentive for the investigation. Furthermore, it presents a problem that can be handled satisfactorily by experimental treatment. (2) In the second set of investigations the colors were made equal in saturation. These determinations are important particularly in colorimetry and in the fields to which that type of rating or of specifying color is applied. (3) In a third set of investigations the lights were made equal in energy. These determinations alone give results which express the true selectiveness of the adaptation process to time of exposure.

The ways in which the stimuli have been equalized include, it will be noted, all the ways, objective and subjective, in which the amount of colored light may be specified. This served as a more general reason for conducting the experiment under the conditions given above.

With regard to the procedure, it will be recalled (a) that the threshold method is used throughout this investigation in order to

ascertain the decay of sensitivity of the eye's response to spectrum lights; (b) that the amount of light required to arouse the chromatic sensation is determined after fatiguing the eye to the full intensity of the light whose threshold value is to be determined; (c) that these threshold values are determined after fatigue periods of 0, 2, 5, 10, 20, 30, 40, 50, 60, 120, 180, 240, and 300 seconds, by reducing the amount of light stimulating the eye; and (d) that this reduction is accomplished by the use of adjustable sectored discs introduced into the beam of light used

TABLE VI. Light Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 12.5 m.c.

Fatigue period	——Threshold energy values in terms of watt $\times 10^{-13}$——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	571.804	15.2404	33.4027	156.830
2	978.814	59.3576	100.0487	364.790
5	1728.675	109.5801	188.8417	525.296
10	3457.350	236.5103	330.1602	780.651
20	8451.300	335.1324	559.0220	1123.553
30	13967.815	441.9730	695.5884	1459.160
40	18131.880	529.6372	807.8931	1750.992
50	22664.850	603.6035	935.4546	2057.416
60	26852.085	651.0883	1063.0172	2320.064
120	40182.090	774.3659	1385.6737	3582.258
180	45752.265	842.8534	1428.1949	4319.112
240	47941.920	911.3409	1435.6980	4713.087
300	49055.955	960.6521	1450.7020	4931.959

TABLE VII. Light Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 25 m.c.

Fatigue period	——Threshold energy values in terms of watt $\times 10^{-13}$——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	571.804	15.2404	33.4027	156.830
2	1220.000	60.7455	115.355	416.609
5	2779.259	127.775	230.711	995.202
10	4677.234	258.360	426.4037	1400.655
20	9083.240	387.514	737.451	1916.686
30	14988.200	511.100	1063.920	2358.999
40	20335.780	632.591	1262.732	2672.303
50	27317.355	754.082	1458.425	3133.045
60	33621.360	906.993	1647.937	3446.350
120	55855.640	1499.785	2183.517	5971.236
180	65752.418	1780.471	2278.273	8127.488
240	70226.260	1868.447	2302.992	9177.480
300	72869.950	1920.814	2315.352	9952.026

for fatiguing the eye, immediately at the end of the fatiguing period. The results in their original form were in terms of degrees of open sector of the rotating discs, adjusted to give the chromatic threshold. From these data and from the total energy value of the beam of light entering the eye, given in Table V, the threshold values in terms of the energy of the various spectrum lights at the eye were obtained. These are given in Tables VI–VIII for light adaptation and IX–XI for dark adaptation, when the lights were made equal photometrically at 12.5, 25, and 40

TABLE VIII. Light Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 40 m.c.

Fatigue period	——Threshold energy values in terms of watt $\times 10^{-13}$——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	571.804	15.240	33.402	156.830
2	1736.835	68.453	173.328	518.663
5	3705.352	146.032	332.971	1106.480
10	6021.196	273.830	538.228	1548.030
20	11347.639	438.096	1058.210	2143.805
30	15863.536	830.557	1345.569	2939.088
40	21758.990	1204.764	1587.315	3492.328
50	28716.540	1460.320	1815.378	4149.300
60	37285.024	1706.749	2098.175	4840.850
120	64843.520	2774.608	3362.025	8298.600
180	80128.220	3112.307	3867.940	10788.180
240	94023.293	3286.720	4296.695	13001.140
300	99349.735	3367.863	4561.250	14937.480

TABLE IX. Dark Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 12.5 m.c.

Fatigue period	——Threshold energy values in terms of watt $\times 10^{-13}$——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	45.044	2.100	1.595	20.132
2	153.660	3.655	5.002	65.662
5	460.980	7.305	10.005	124.029
10	998.790	17.350	25.012	196.987
20	2304.901	42.006	40.192	313.719
30	3764.670	62.096	60.002	452.340
40	5224.442	83.587	75.036	554.479
50	6376.890	100.448	86.292	620.143
60	7452.511	124.191	100.049	693.101
120	12139.143	208.202	212.603	1021.411
180	14905.023	286.734	305.148	1284.060
240	17440.410	347.004	352.672	1561.301
300	19822.144	373.485	378.934	1838.541

meter-candles respectively. For the lights made equal in saturation, the threshold values are given in Table XII for the light-adapted eye and in Table XIII for the dark-adapted eye. Tables XIV and XV give the threshold values for light and dark adaptation respectively when the lights are equalized in energy.

Sensitivity is usually considered as varying directly with the amount of response and inversely as the amount of stimulus required to produce the response. In the present case, sensitivity is taken as the reciprocal of the energy value of the light required

TABLE X. Dark Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 25 m.c.

Fatigue period	——Threshold energy values in terms of watt × 10^{-13}——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	45.044	2.100	1.595	20.132
2	338.930	4.608	5.356	106.892
5	745.646	8.379	11.948	202.726
10	1586.192	23.041	26.779	368.594
20	3253.720	50.272	49.437	626.609
30	4880.561	85.882	67.977	792.476
40	6575.242	117.302	80.637	884.625
50	8405.460	150.817	115.356	1068.921
60	9761.161	186.426	148.314	1179.499
120	15861.922	326.769	329.588	1658.671
180	19153.303	423.123	457.304	2064.924
240	23046.900	504.721	535.580	2524.867
300	24470.746	555.193	585.018	2838.170

TABLE XI. Dark Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The faitguing lights were made equal photometrically at 40 m.c.

Fatigue period	——Threshold energy values in terms of watt × 10^{-13}——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	45.044	2.100	1.595	20.132
2	347.377	6.389	6.386	138.310
5	926.338	14.603	18.245	242.043
10	2084.260	31.945	31.929	414.930
20	3589.552	63.889	58.474	760.705
30	5553.018	95.834	77.541	1106.480
40	7410.703	127.778	104.909	1417.678
50	8916.003	164.286	136.838	1728.875
60	10189.718	205.358	173.328	1936.341
120	17368.834	410.715	456.125	2800.778
180	23621.615	547.620	647.697	3596.060
240	26169.044	638.890	766.290	4356.765
300	27326.967	684.525	839.270	4840.851

to arouse just noticeable chromatic sensation. Because of the wide range of the values obtained, however, all of the curves and graphs are plotted in terms of the logarithm of the reciprocals.

Since the values of light required to arouse the initial threshold sensation are equal for the same wave-lengths of light and state of adaptation of the eye, whatever intensity of light is used as the fatiguing stimulus, one may make intercomparisons of the results representing the loss of sensitivity due to fatigue for the same wave-length at all intensities of light. But since the initial sensi-

TABLE XII. Light Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in saturation to the yellow (579 mμ) at 25 m.c.

Fatigue period	——Threshold energy values in terms of watt × 10^{-13}——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	571.804	15.240	33.402	156.881
2	3341.123	60.745	504.181	383.859
5	5385.300	127.775		532.395
10	5477.250	258.361		747.690
20	6088.876	387.5143		1023.066
30	6344.481	511.100		1154.913
40	6444.596	632.591		1183.286
50	6558.217	754.082		1194.968
60	6572.700	906.993		1201.644
120		1499.785		
180		1780.471		
240		1868.447		
300		1920.814		

TABLE XIII. Dark Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in saturation to the yellow (579 mμ) at 25 m.c.

Fatigue period	——Threshold energy values in terms of watt × 10^{-13}——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	45.044	2.100	1.595	20.132
2	296.684	4.608	3.485	50.069
5	497.517	8.379	5.633	88.454
10	912.875	23.041	9.176	160.292
20	1844.008	50.272	14.896	333.379
30	2857.200	85.882	19.746	514.037
40	3806.689	117.302	24.275	679.263
50	4692.174	150.817	27.934	821.125
60	5203.345	186.426	30.315	891.219
120	5582.231	326.769	37.168	979.674
180	5751.111	423.123	40.362	1041.425
240	5851.529	504.721	41.587	1058.114
300	5879.140	555.193	41.814	1064.790

tivity differs from wave-length to wave-length of light, no quantitative intercomparisons can be made of the results expressing loss of sensitivity for the different wave-lengths even within the same intensity series. In order to make possible some intercomparison for different wave-lengths, the results are presented also in terms of percentage increase in the energy of light needed to arouse the threshold sensation at the end of the different intervals of adaptation, using in each case the threshold value for the fresh eye as the base on which to compute the percentage increase.

TABLE XIV. Light Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in energy to green (515 mμ) at 40 m.c.

Fatigue period	——Threshold energy values in terms of watt × 10^{-13}——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	571.804	15.240	33.402	156.830
2	3341.123	65.153	173.328	282.991
5	5385.300	114.352	332.971	383.408
10	5477.250	274.143	538.228	511.210
20	6088.876	442.069	1058.210	803.330
30	6344.481	793.920	1345.569	1000.144
40	6444.896	1168.324	1587.315	1364.748
50	6558.217	1389.360	1815.378	1629.482
60	6572.700	1614.903	2098.175	1880.523
120		2670.457	3362.025	2797.962
180		2986.218	3867.940	3286.350
240		3144.099	4296.698	3806.689
300		3175.677	4561.250	3993.828

TABLE XV. Dark Adaptation

Showing the energy values of spectrum lights at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in energy to green (515 mμ) at 40 m.c.

Fatigue period	——Threshold energy values in terms of watt × 10^{-13}——			
in seconds	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	45.044	2.100	1.595	20.132
2	296.684	6.315	6.386	54.773
5	497.517	13.533	18.245	118.674
10	912.875	27.066	31.929	182.575
20	1844.008	54.832	58.474	301.249
30	2857.299	90.220	77.541	438.180
40	3806.689	112.773	104.909	522.388
50	4692.174	144.352	136.838	565.983
60	5203.345	193.969	173.328	611.626
120	5582.251	369.894	456.125	867.231
180	5751.111	496.199	647.698	1086.321
240	5851.529	572.885	766.290	1278.025
300	5879.140	631.528	839.270	1414.956

In the presentation of the results, the three principal divisions of the problem will be treated separately, namely, spectrum lights made equal photometrically at 12.5, 25, and 40 meter-candles, spectrum lights made equal in saturation to the yellow at 25 meter-candles, and spectrum lights made equal in energy to the green at 40 meter-candles. Also for each of these, two subdivisions will be made: one for the loss of sensitivity, the other showing the percentage loss of sensitivity or the inverse, the percentage increase in the energy of light required to arouse the threshold sensation at the end of each of the periods of stimulation.

A. The Lights Made Equal Photometrically

1. *Loss of Sensitivity.*

The sensitivity of the eye at the end of the different periods of adaptation employed, in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation, are presented in Tables XVI–XVIII for light adaptation and in Tables XIX–XXI for dark adaptation. The results in these tables are represented graphically in Figures 6–15. The curves shown in these figures are grouped in two ways. In Figures 6–11, inclusive, the curves for the four colors for one intensity of light are plotted in one chart; in Figures 12–15, inclusive, the curves

TABLE XVI. Light Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 12.5 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	10.243	11.817	11.476	10.805
2	10.009	11.227	11.000	10.438
5	9.762	10.960	10.724	10.280
10	9.461	10.626	10.481	10.108
20	9.073	10.475	10.253	9.949
30	8.855	10.355	10.158	9.836
40	8.742	10.276	10.093	9.757
50	8.645	10.219	10.029	9.697
60	8.571	10.186	9.973	9.635
120	8.396	10.111	9.958	9.446
180	8.340	10.074	9.845	9.365
240	8.319	10.040	9.843	9.327
300	8.309	10.017	9.839	9.307

for one color at the three intensities of light and both states of adaptation of the eye, light and dark, are shown on the same chart.

An inspection of the curves in Figures 6–11 reveals the following results: (1) The sensitivity of the fresh eye to the four colors is in the order, from greatest to least, of yellow, green, blue, red. (2) The rate of loss of sensitivity due to fatigue is at first very rapid. As the time of exposure is increased, the rate of loss is increasingly slower, becoming very slow after a period of one minute. (3) The relative rates of loss of sensitivity through a

TABLE XVII. Light Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 25 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	10.243	11.817	11.476	10.805
2	9.914	11.216	10.938	10.380
5	9.556	10.893	10.637	10.002
10	9.330	10.588	10.370	9.853
20	9.042	10.412	10.132	9.717
30	8.826	10.291	9.973	9.627
40	8.692	10.199	9.898	9.573
50	8.564	10.123	9.836	9.504
60	8.473	10.042	9.783	9.463
120	8.253	9.824	9.661	9.224
180	8.182	9.750	9.642	9.090
240	8.153	9.729	9.638	9.037
300	8.137	9.716	9.636	9.002

TABLE XVIII. Light Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 40 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	10.242	11.817	11.476	10.804
2	9.760	11.265	10.761	10.285
5	9.431	10.836	10.478	9.956
10	9.220	10.563	10.269	9.810
20	8.944	10.358	9.976	9.669
30	8.800	10.081	9.871	9.532
40	8.662	9.919	9.799	9.457
50	8.542	9.836	9.741	9.382
60	8.428	9.768	9.678	9.315
120	8.188	9.557	9.473	9.081
180	8.096	9.507	9.413	8.967
240	8.027	9.483	9.367	8.886
300	8.003	9.473	9.341	8.826

period of five minutes do not change the order of ranking as to sensitivity from the above for any of the colors except green and yellow under dark adaptation. That is, with this exception, if we compare the sensitivity of the eye to the four spectrum lights at each of the brightness levels at any time from the beginning to the end of the five-minute period, we find the order to be yellow, green, blue, and red. This order does not hold, however, for yellow and green for the dark-adapted eye. Under dark adaptation the eye changes its relative sensitivity to these two colors with different

TABLE XIX. Dark Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 12.5 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	11.346	12.678	12.797	10.696
2	10.813	12.437	12.301	11.183
5	10.336	12.136	12.000	10.906
10	10.001	11.761	11.602	10.706
20	9.637	11.377	11.396	10.503
30	9.424	11.207	11.222	10.345
40	9.281	11.078	11.125	10.256
50	9.195	10.998	11.064	10.208
60	9.128	10.906	11.000	10.159
120	8.916	10.682	10.672	9.991
180	8.827	10.543	10.516	9.891
240	8.758	10.460	10.455	9.817
300	8.702	10.428	10.428	9.735

TABLE XX. Dark Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 25 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	11.346	12.678	12.797	11.696
2	10.470	12.336	12.271	10.971
5	10.127	12.077	11.923	10.693
10	9.800	11.638	11.572	10.433
20	9.488	11.299	11.306	10.203
30	9.311	11.066	11.168	10.101
40	9.182	10.930	11.143	10.053
50	9.075	10.822	10.938	9.971
60	9.010	10.730	10.829	9.928
120	8.800	10.486	10.482	9.780
180	8.718	10.374	10.340	9.685
240	8.637	10.297	10.271	9.598
300	8.631	10.256	10.233	9.547

lengths of exposure for all three intensities of light employed. This is shown in Figures 9–11 by the crisscrossing of the curves for yellow and green. This crisscrossing occurs after approximately the same length of time for the different intensities of light used. During the first 20 seconds of exposure to these lights, the eye is considerably more sensitive to yellow; between 20 and 30 seconds, the excess of sensitivity to yellow is slight; after 30 seconds, the sensitivity for a time is greater to green; at a point between 90 and 110 seconds, the curves again intersect, the sensitivity becoming greater to yellow; and from this time on to the end of the five-minute period the trend of the curves is slightly different. For the lowest of the three intensities, 12.5 meter-candles, they again converge to a common point at the end of five minutes; for the second intensity, 25 meter-candles, they also converge but do not meet; while for the highest intensity, 40 meter-candles, they are still diverging at the end of the five-minute period. The shape of the curves for this latter part of the period seems to indicate that had an intensity lower than 12.5 meter-candles been used, the curve for green might again have passed below the curve for yellow. (4) Fatigue tends to decrease the difference in sensitivity to yellow, green, and blue for all intensities of light, both under dark and light adaptation. It tends, however, to increase the difference in sensitivity between these

TABLE XXI. Dark Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 40 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	11.346	12.678	12.797	11.696
2	10.459	12.195	12.195	10.859
5	10.033	11.836	11.739	10.616
10	9.681	11.496	11.496	10.382
20	9.445	11.195	11.233	10.119
30	9.255	11.018	11.110	9.956
40	9.130	10.893	10.979	9.848
50	9.050	10.784	10.864	9.762
60	8.992	10.687	10.761	9.713
120	8.760	10.386	10.341	9.553
180	8.627	10.262	10.189	9.444
240	8.582	10.195	10.115	9.361
300	8.563	10.165	10.076	9.315

colors and red. This phenomenon is more marked for the dark than for the light-adapted eye. For a time the difference increases progressively with increase of length of exposure and then it decreases. In some cases, particularly for the dark-adapted eye, the decrease is very slow. This relatively rapid rate of fatigue to red as compared with yellow has an important bearing on the explanation of the change of hues of mixed colors made up of red and yellow. These colors all change progressively towards yellow as the result of fatigue. It also has a bearing on the explanation of the change of spectrum red toward yellow as the result of adaptation or fatigue. Spectrum red arouses two excitations in the retina, red strongly and yellow weakly. The superior strength of the red component which would cause a faster rate of adaptation because of its intensity alone, together with the greater effect of red on loss of sensitivity, causes the relative proportions of the two components to change and the hue of the red to tend towards yellow.

With regard to the curves shown in Figures 12–15, the curves grouped to show the effect of the photometric intensity of light on the comparative loss of sensitivity to each color for each state of adaptation, the following results may be pointed out: (1) Photometric intensity or brightness is an important factor in the cause of the eye's loss of chromatic sensitivity. In general, the greater the intensity, the greater was the eye's loss of sensitivity in any given period of time. Doubtless this is due to the greater physical intensity of the lights which measure higher photometrically, not to any effect of the brightness or achromatic component on the loss of chromatic sensitivity. (2) State of adaptation is not only an important factor in the chromatic sensitivity of the fresh eye but also in its liability to loss of sensitivity as the result of fatigue. That is, the chromatic sensitivity of the eye to the spectrum lights was not only greater under dark than under light adaptation but the loss of sensitivity for red, green, and yellow, for any given period of time, was considerably greater under dark adaptation. For blue, the total loss of sensitivity at the end of the five-minute period was more nearly the same under light and dark adaptation. (3) So much greater was the sensitivity of the eye under dark

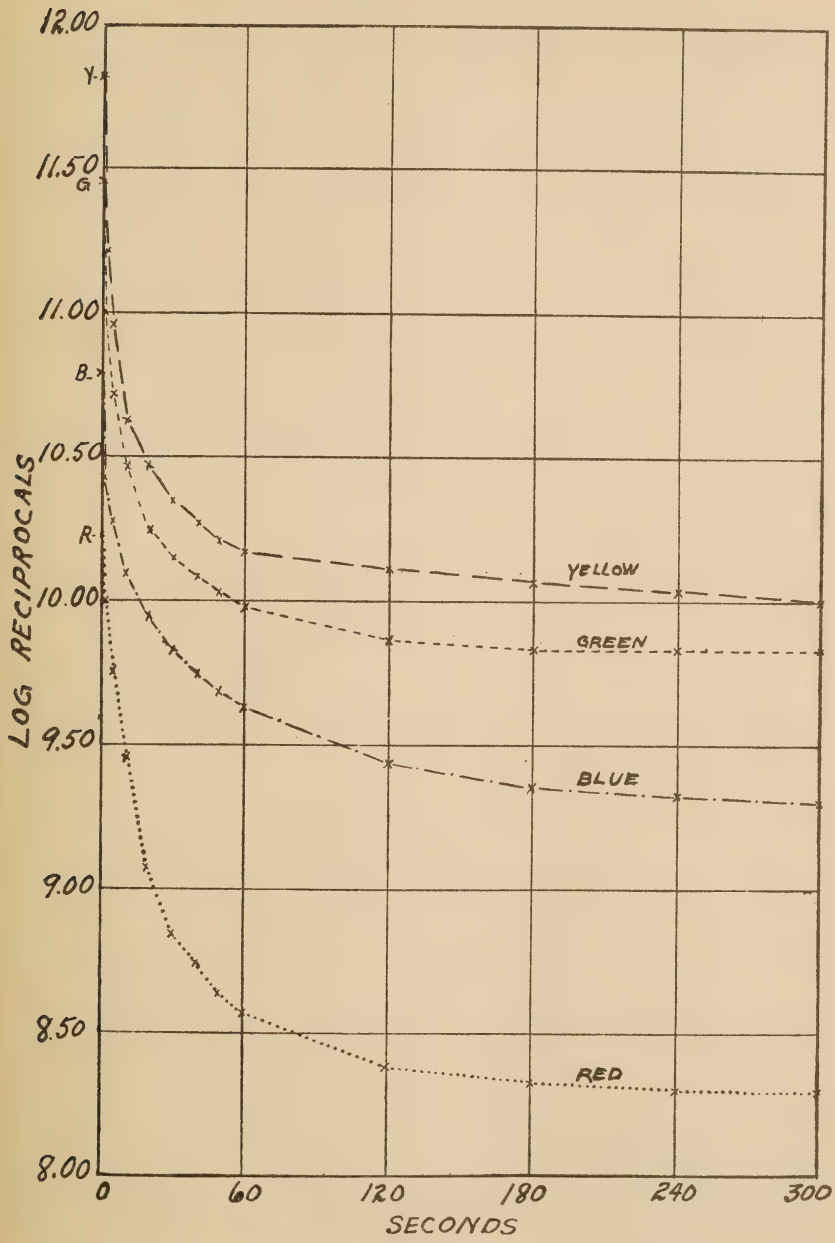

Fig. 6.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green and blue, made equal photometrically at 12.5 meter-candles.

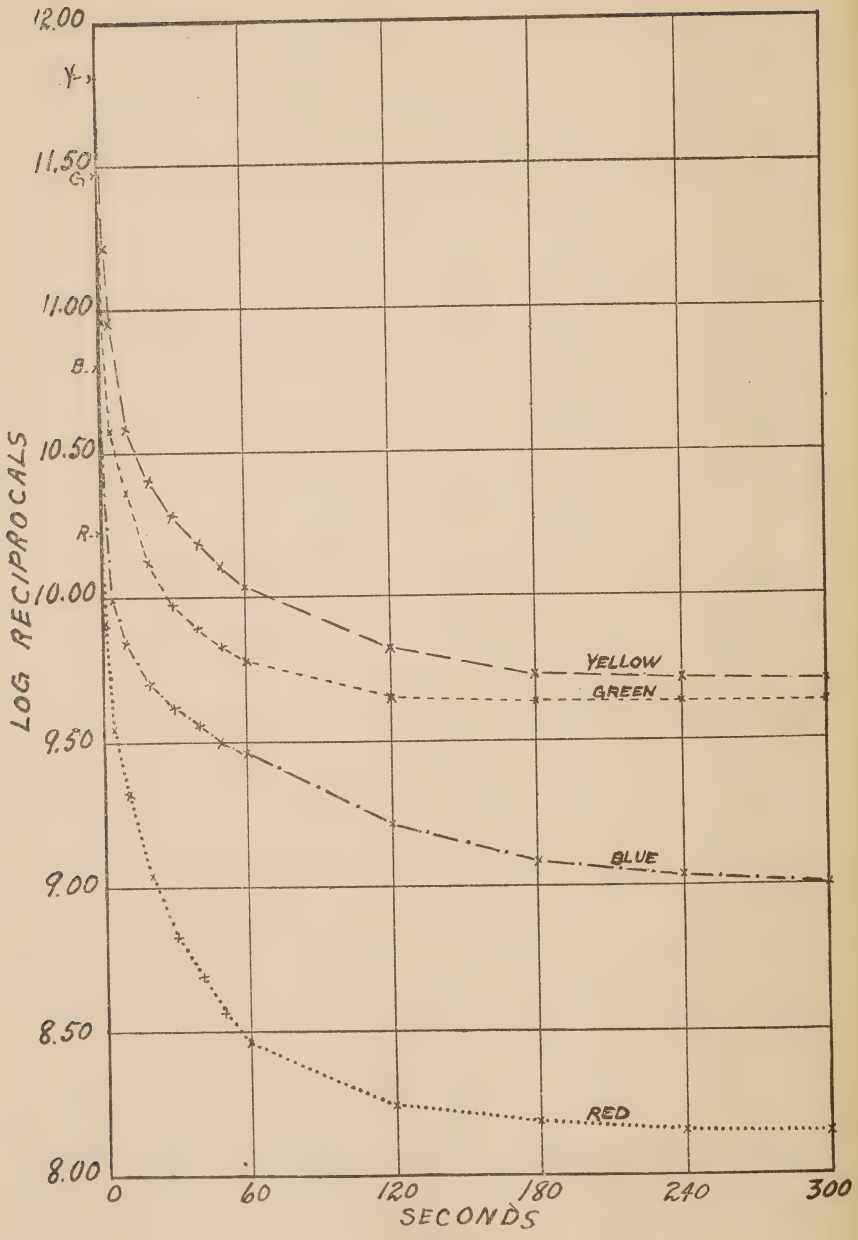

FIG. 7.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green and blue, made equal photometrically at 25 meter-candles.

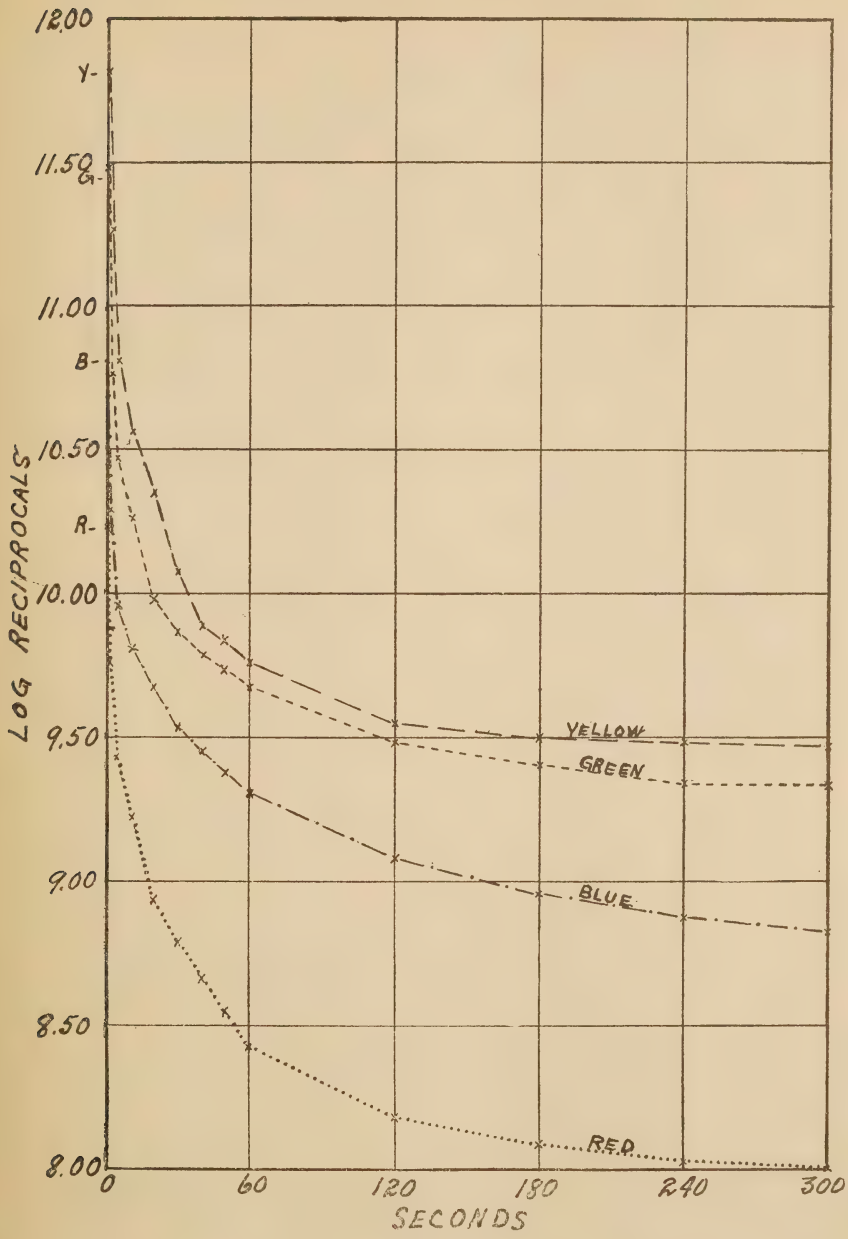

FIG. 8.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green and blue, made equal photometrically at 40 meter-candles.

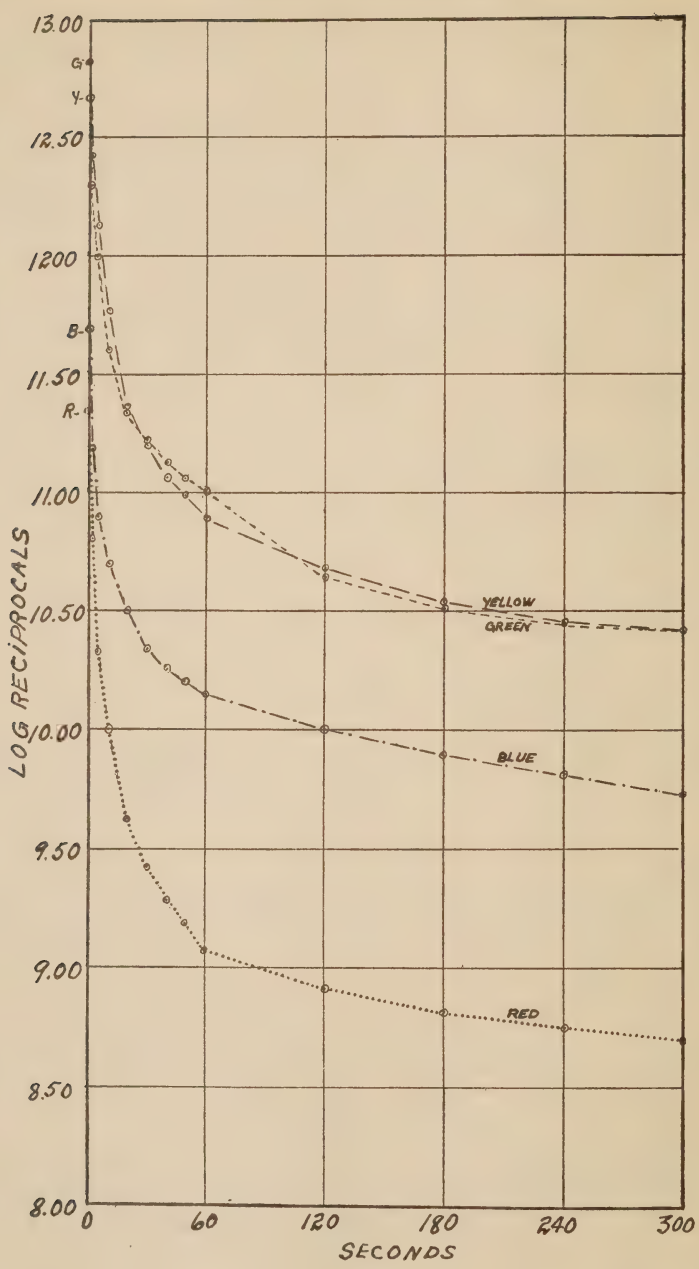

FIG. 9.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green and blue, made equal photometrically at 12.5 meter-candles.

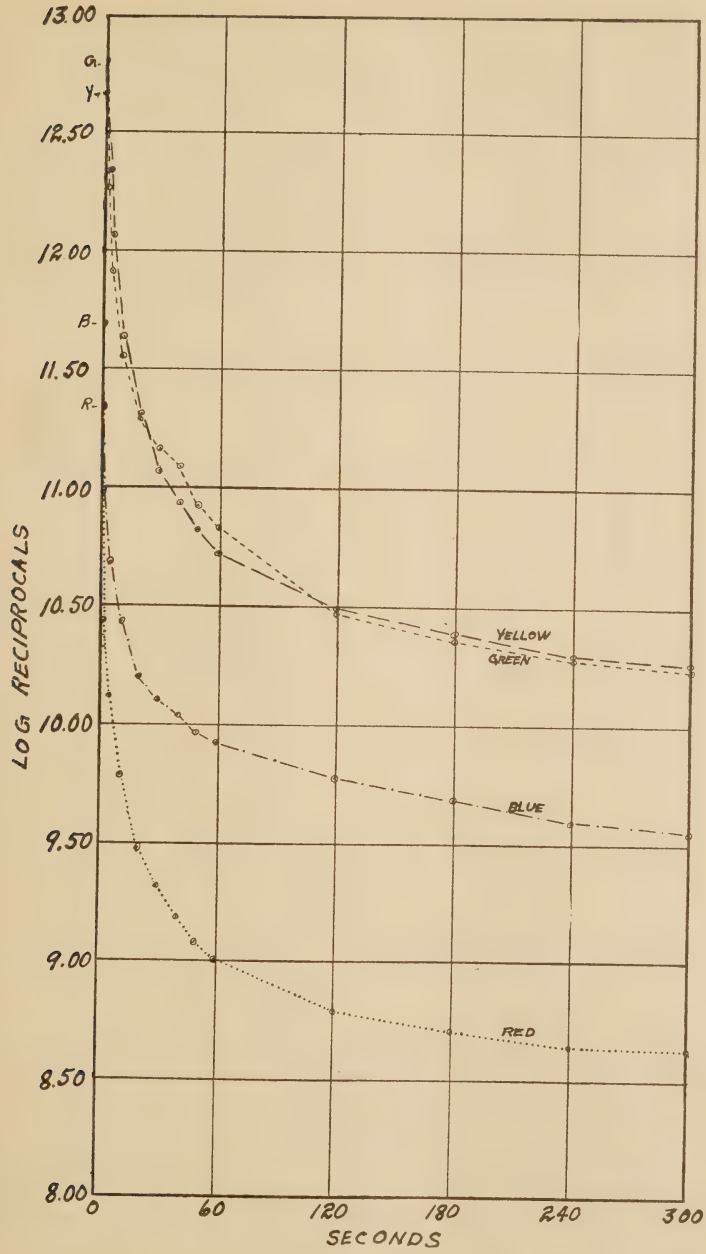

FIG. 10.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green and blue, made equal photometrically at 25 meter-candles.

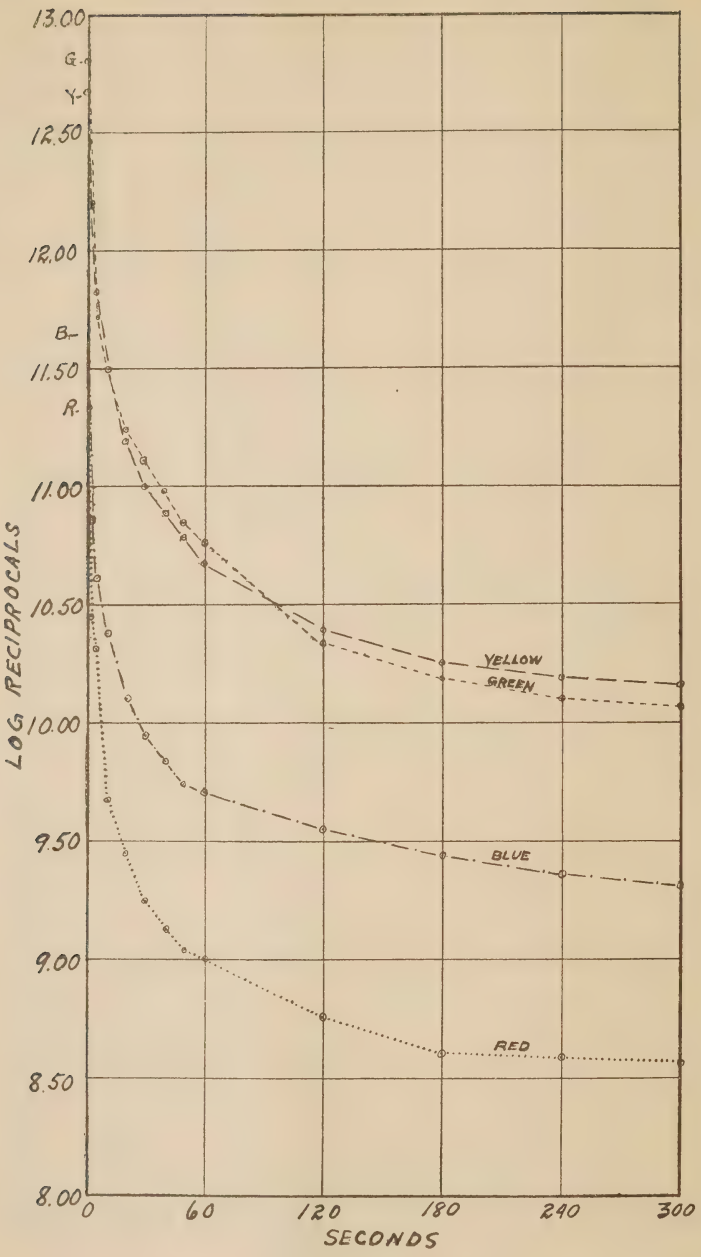

FIG. 11.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green and blue, made equal photometrically at 40 meter-candles.

adaptation that when fatigued for any of the lights at the highest intensity employed it never fell below that of the light-adapted eye fatigued for the same length of time at the lowest intensity of light employed. (4) Fatigue exerted a marked tendency to decrease the difference in the sensitivity of the eye under dark and light adaptation. The decrease in the amount of the difference was progressive as the length of the period of exposure was increased, but the ratio or percentage decrease became smaller as the time of exposure became longer. The effect of fatigue on decreasing

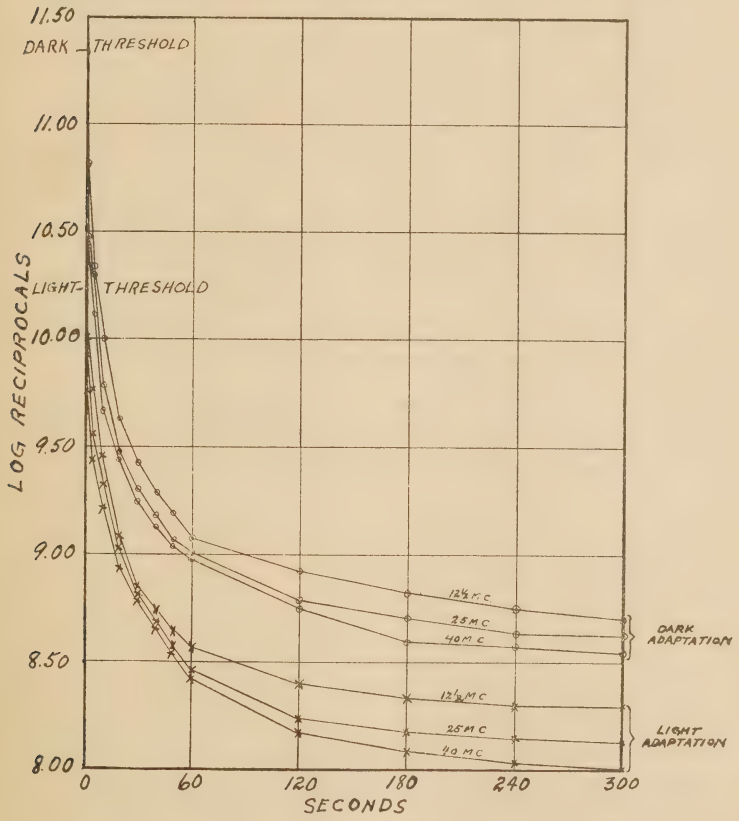

Fig. 12.

Showing loss of sensitivity for red at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

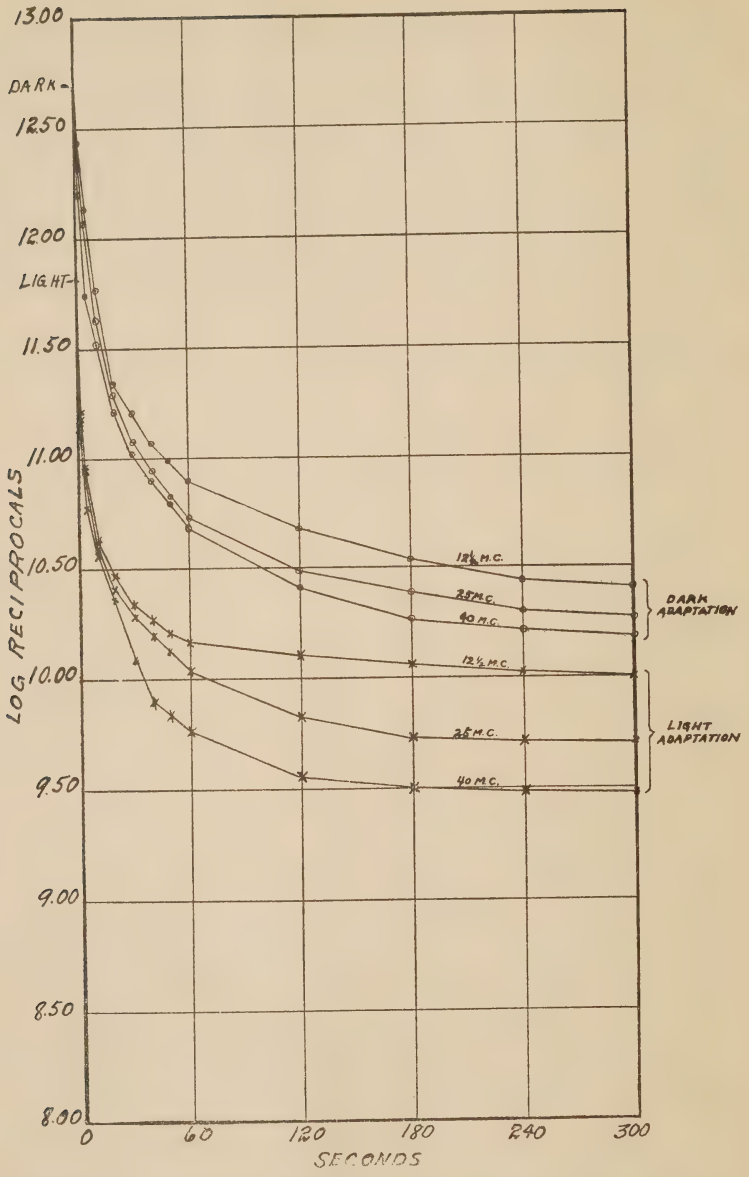

FIG. 13.

Showing loss of sensitivity for yellow at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

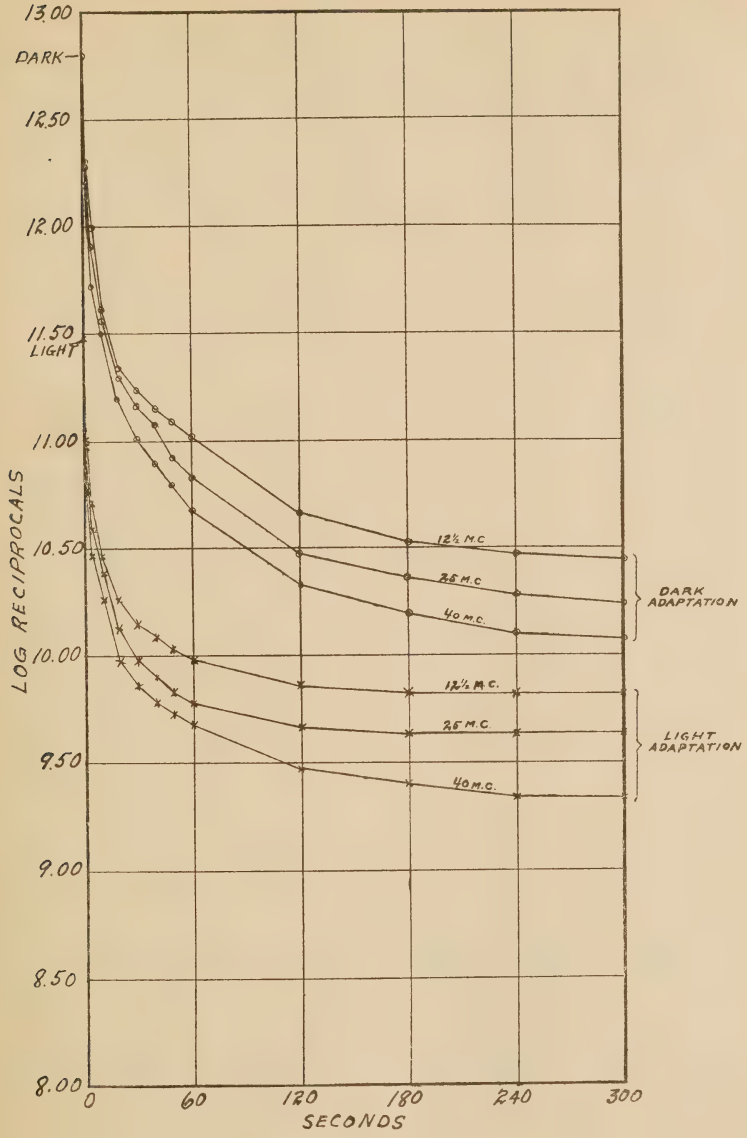

FIG. 14.

Showing loss of sensitivity for green at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

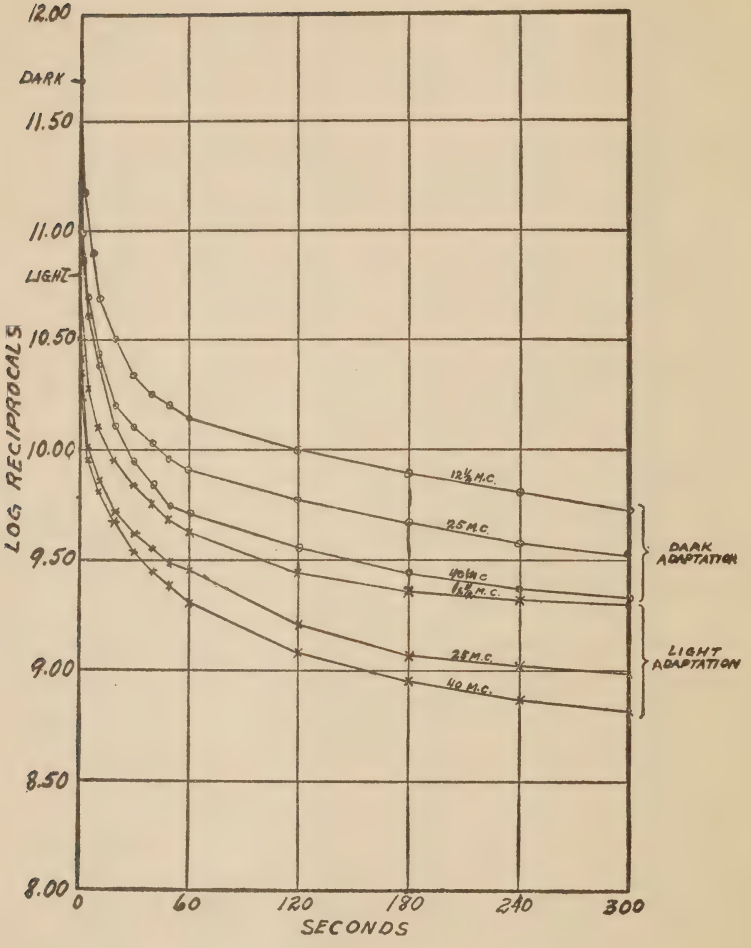

FIG. 15.

Showing loss of sensitivity for blue at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

this difference in sensitivity to the four colors was from greatest to least, yellow, green, blue, red. Moreover, we found that the amount of difference became progressively less with decrease of intensity. That is, the difference in the eye's sensitivity to the same wave-length, under conditions of dark and light adaptation, was less for the spectrum lights at 12.5 meter-candles than at 25 meter-candles, and less for those at 25 meter-candles than at 40 meter-candles.

2. *Percentage Increase of Light Required to Arouse the Threshold Sensation.*

Since the initial sensitivity, that is, the sensitivity of the fresh eye, varies from wave-length to wave-length, the curves showing loss of sensitivity may lead to erroneous conclusions, if they are inspected casually. For example, in Figure 6 the final sensitivity to blue is much less than that to yellow, but the loss of sensitivity is by no means as great. Correct interpretation can be made only if there is a common point of reference. Further, the relative rates of loss of sensitivity to the different colors at different times during the course of adaptation are not easily judged from the curves plotted to represent sensitivity. Rate of change can be seen readily only in curves plotted to show ratio or percentage change. Plots of this kind could be made in two ways: (a) The percentage decrease in sensitivity computed on the initial sensitivity as base could be plotted, or (b) the percentage increase in the energy values of light required to arouse the various threshold sensations computed on the value required to arouse the initial threshold sensation could be used. The latter of these two methods has been chosen for our representation here. The relative rates of loss of sensitivity could readily be told from an inspection of either.

The results of these computations are shown in Tables XXII–XXVII and in the curves given in Figures 16–32. These curves have been grouped in four ways. In Figures 16–21 the curves for the four colors for one intensity of light are plotted on one chart. Length of fatigue period for each color is plotted on the horizontal coördinate and percentage increase of energy required

to arouse the threshold sensation on the vertical coördinate. These curves are intended to make convenient a direct comparison of the difference in the percentage increase in the energy required to arouse the threshold sensation for each of the four colors for each length of fatigue period. In these figures there are as many different curves as there are colors used.

In Figures 22–25 the curves for one color at the three intensities of light for both light and dark adaptation are plotted on the same chart. Again length of fatigue period for each color is plotted on the horizontal coördinate and percentage increase of energy required to arouse the threshold sensation on the vertical

TABLE XXII. Light Adaptation

Showing percentage increase in the energy value of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 12.5 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	71	289	199	133
5	201	619	463	235
10	504	1449	888	334
20	1379	2099	1571	616
30	2345	2801	1979	829
40	3063	3372	2314	1014
50	3868	3857	2697	1212
60	4586	4172	3080	1378
120	6930	4979	4037	2182
180	7892	5425	4156	2654
240	8228	5878	4186	2903
300	8470	6199	4216	3043

TABLE XXIII. Light Adaptation

Showing percentage increase in the energy value of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 25 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	113	298	245	166
5	385	738	589	535
10	716	1594	1175	791
20	1489	2440	2105	1123
30	2503	3254	3080	1404
40	3448	4048	3778	1605
50	4673	4848	4261	1898
60	5775	5852	4829	2099
120	9669	9742	6429	3707
180	11401	11578	6713	5085
240	12188	12136	6772	5755
300	12653	12497	6817	6249

coördinate. These curves are intended to make convenient a direct comparison of the difference in the percentage increase of energy required to arouse the threshold sensation for each color at the three intensities of light and for both states of adaptation of the eye.

In Figures 26–28 the curves for the four colors at one intensity of light and for both states of adaptation are also plotted on the same chart. In these curves, however, wave-length of light is plotted on the horizontal coördinate and percentage increase of energy required to arouse the threshold sensation on the vertical coördinate. These curves enable one easily to make a cross com-

TABLE XXIV. Light Adaptation

Showing percentage increase in the energy value of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 40 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	203	349	419	231
5	548	856	597	605
10	954	1695	1510	887
20	1873	2775	3050	1263
30	2660	5346	3917	1774
40	3693	7806	4635	2124
50	4918	9479	5322	2546
60	6423	11742	6174	2986
120	11235	18106	9957	5193
180	13913	20303	11452	6763
240	16345	21451	12737	8166
300	17273	21976	13545	9378

TABLE XXV. Dark Adaptation

Showing percentage increase in the energy value of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 12.5 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	242	74	214	226
5	924	247	527	517
10	2118	719	1467	880
20	5017	1899	2420	1456
30	8258	2856	3662	2147
40	11500	3879	4602	2654
50	14053	4684	5317	2982
60	16450	5807	6176	3344
120	26862	9806	13230	4970
180	33078	13566	19061	6262
240	38628	16422	22001	7654
300	43956	17660	23638	9045

parison of the percentage of increase of energy to arouse the threshold sensation for each color for each length of exposure used. In these figures there are as many separate graphs as there were lengths of exposure employed.

The fourth method of presentation is shown in Figures 29–32. Each chart represents one of the four colors at the three intensities for both light and dark adaptation. In these curves intensities are plotted on the horizontal coördinate and percentage increase of energy required to arouse the threshold sensation on the vertical. Each exposure time is represented by a separate graph. By cross comparison these charts show clearly the effect of intensity, time

TABLE XXVI. Dark Adaptation

Showing percentage increase in the energy value of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 25 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values—— Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	·653	119	236	431
5	1556	299	652	910
10	3419	995	1580	1730
20	7126	2294	2997	3012
30	10745	3989	4163	3837
40	14497	5474	5580	4294
50	18559	7092	7178	5219
60	21578	8758	9217	5765
120	35076	15479	20566	8151
180	42402	20040	28591	10139
240	51060	23943	33482	12425
300	54168	26323	36554	14015

TABLE XXVII. Dark Adaptation

Showing percentage increase in the energy value of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal photometrically at 40 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values—— Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	670	204	238	586
5	1956	595	1047	1103
10	4529	1418	1900	1963
20	7859	2942	3568	3683
30	12232	4460	4759	5417
40	16361	5998	6458	6958
50	19691	7711	8465	8449
60	22422	9663	10784	9542
120	38406	19468	28529	13817
180	52392	25990	41633	17793
240	57942	30321	47966	21570
300	60606	32463	52543	23955

of exposure, and state of adaptation on the percentage increase of energy required to arouse the threshold of sensation for each color.

An inspection of these tables and charts reveals the following points: (1) Adaptation or loss of sensitivity as a retinal function

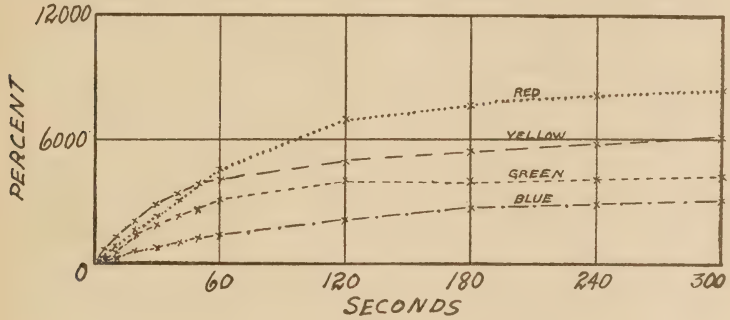

FIG. 16.

Showing percentage increase in energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal photometrically at 12.5 meter-candles for light adaptation.

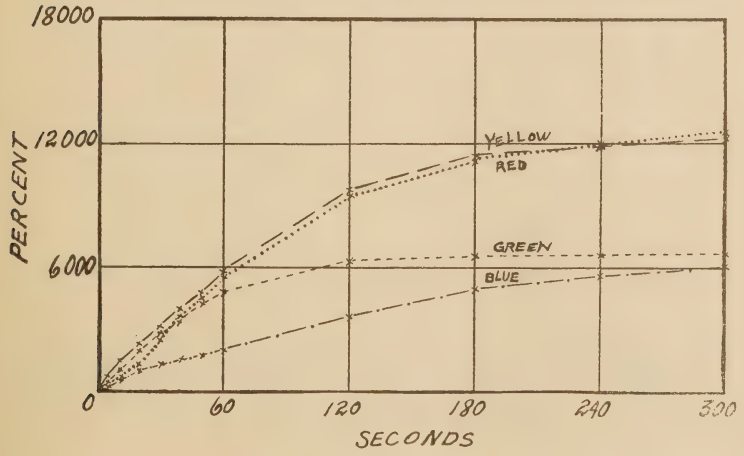

FIG. 17.

Showing percentage increase in energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal photometrically at 25 meter-candles for light adaptation.

shows selectiveness to wave-length, intensity, time of exposure, and state of adaptation of the eye. That is, the rate of loss is different for the different wave-lengths of light. This difference becomes progressively less for each of the wave-lengths as the length of exposure is increased. It becomes progressively greater with increase of intensity of light and is much greater for dark than for light adaptation. For the part of the intensity scale used, rate of adaptation increases with an increase of photometric intensity. The rate of increase, however, is an irregular function of increase of intensity. (2) Not only does the rate of loss differ for the different wave-lengths but the order of ranking as to rate of loss changes with length of exposure, intensity of light, and state of adaptation of the eye. Most of the changes in the order of ranking due to increasing the length of exposure come within the first minute. (3) Ranked as to rate of loss for the light-adapted eye at the photometric intensities 12.5 and 25 meter-

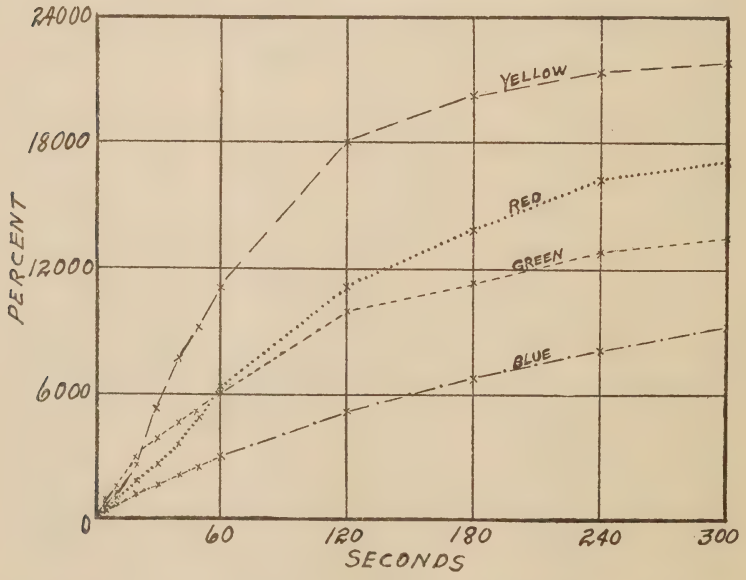

FIG. 18.

Showing percentage increase in energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal photometrically at 40 meter-candles for light adaptation.

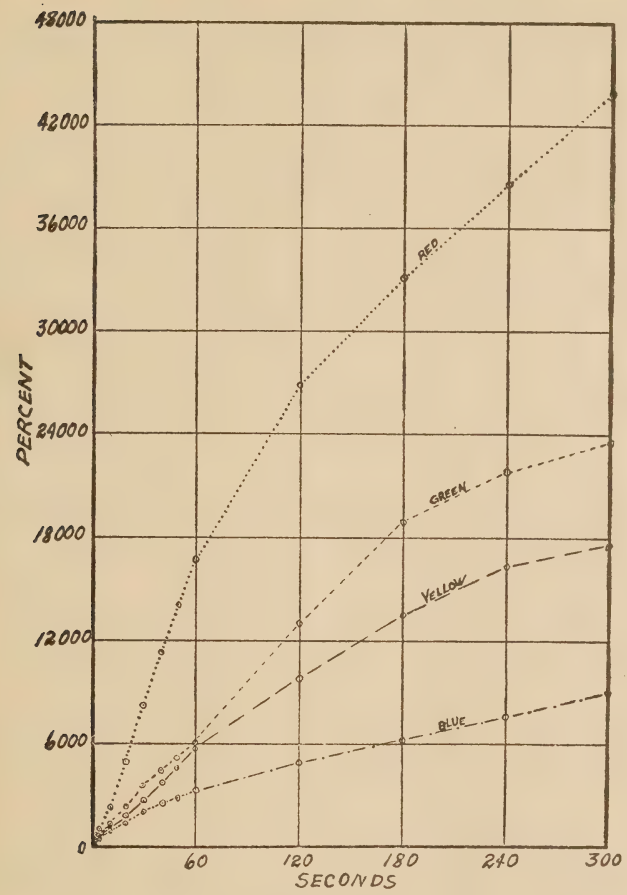

FIG. 19.

Showing percentage increase in energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal photometrically at 12.5 meter-candles for dark adaptation.

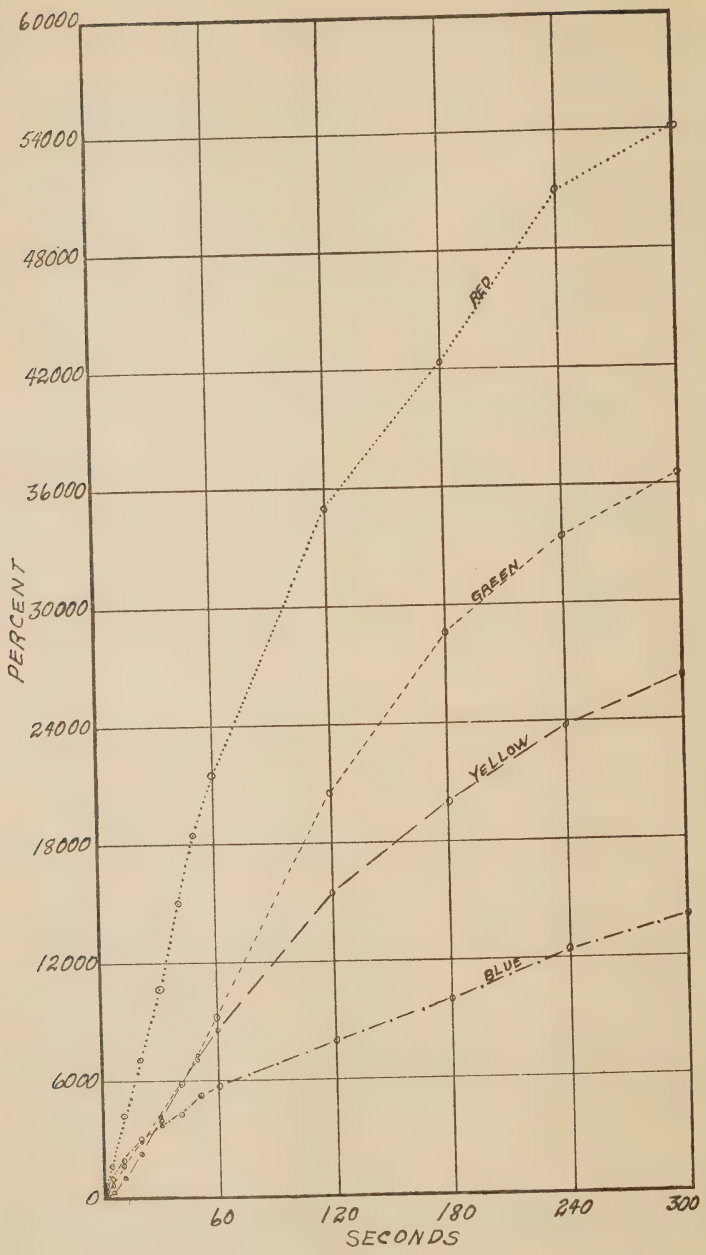

FIG. 20.

Showing percentage increase in energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal photometrically at 25 meter-candles for dark adaptation.

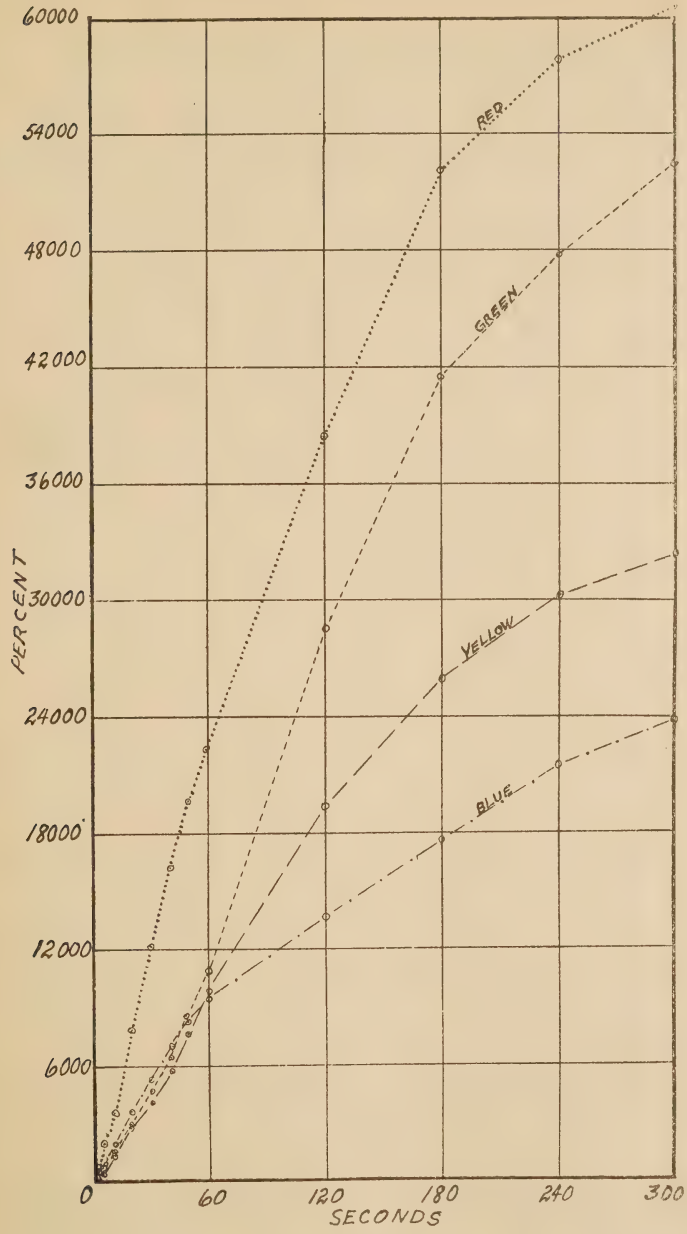

FIG. 21.

Showing percentage increase in energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal photometrically at 40 meter-candles for dark adaptation.

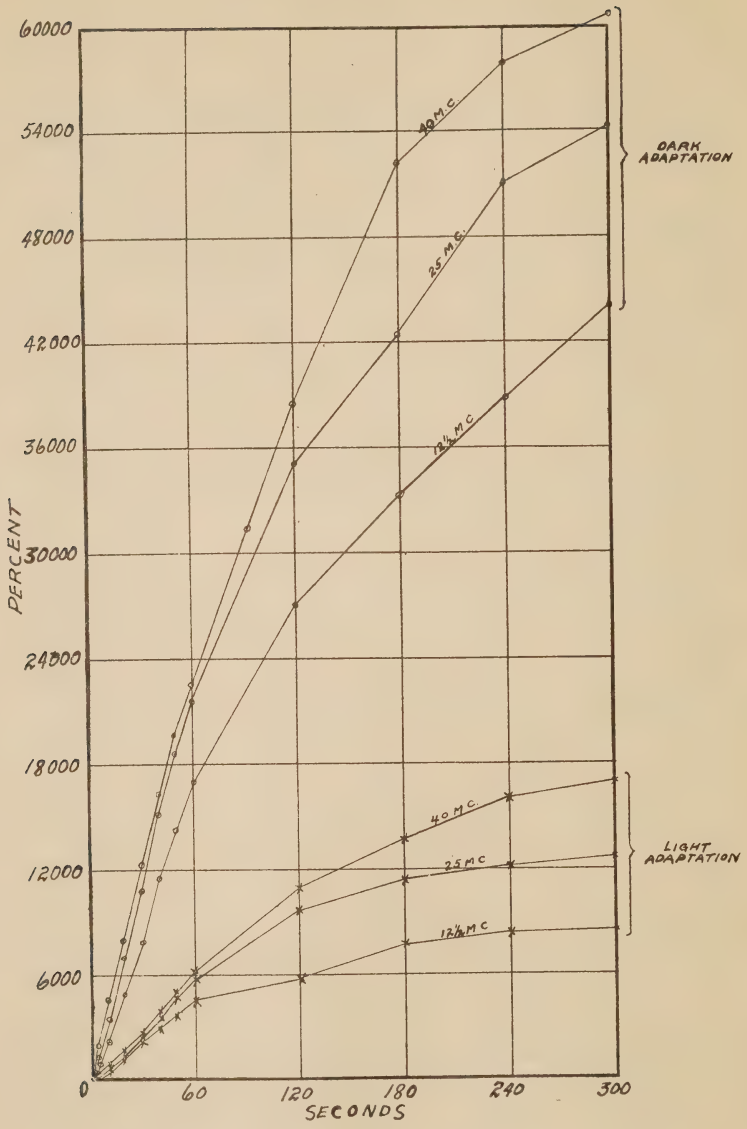

FIG. 22.

Showing the percentage increase in the energy values required to arouse the threshold sensation for red at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

candles, the order from greatest to least is, after the first minute, red, yellow, green, and blue. Within the first minute crisscrossing occurs in the curves for red and yellow at 12.5 meter-candles and for red and green at 25 meter-candles. The curves for red and yellow also intersect at the end of four minutes. At the photometric intensity of 40 meter-candles the order of loss of sensitivity after the first minute, from greatest to least, is yellow, red, green, blue. (4) Ranked as to rate of loss for the dark-adapted eye after one minute of exposure, the order from greatest to least for all of the intensities is red, green, yellow, and blue. Within the first minute several crisscrossings occur in the curves for green, yellow, and blue for the intensities 25 and 40 meter-candles.

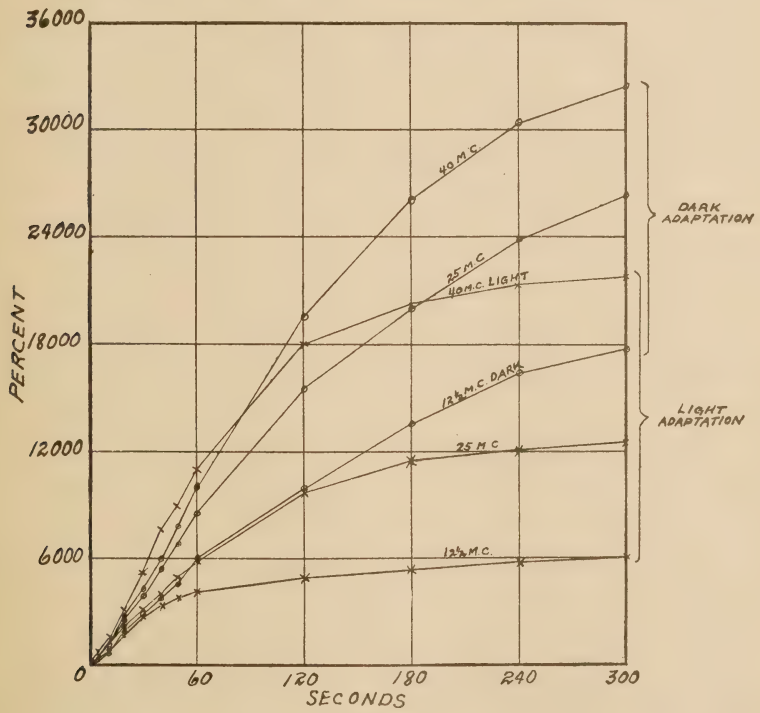

FIG. 23.

Showing the percentage increase in the energy values required to arouse the threshold sensation for yellow at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

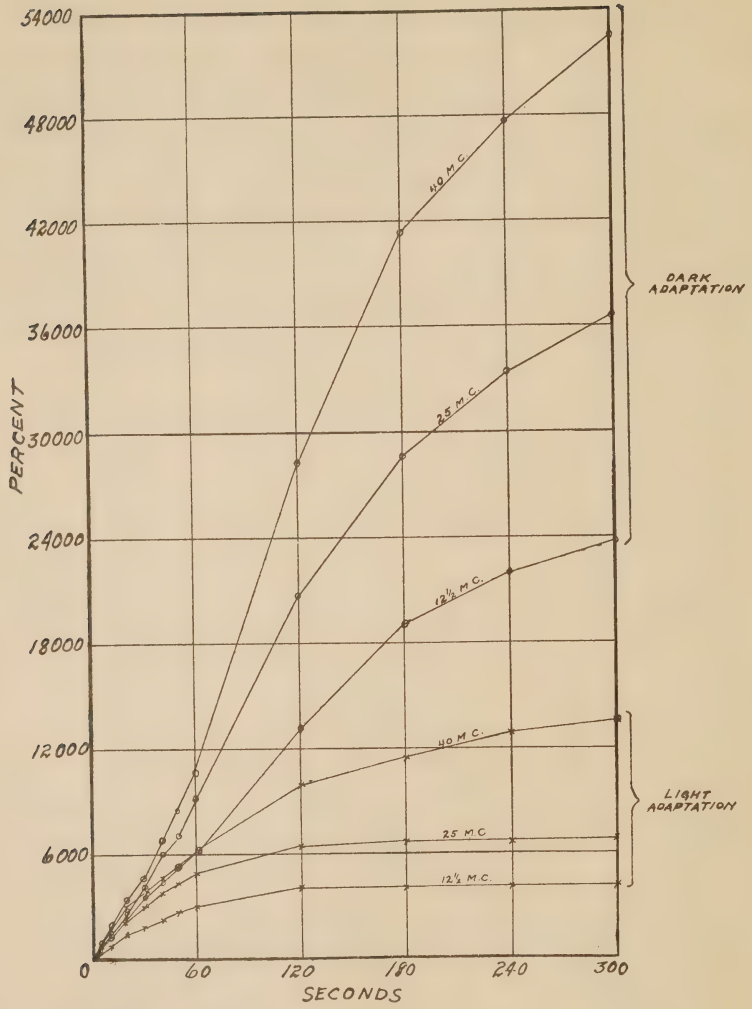

FIG. 24.

Showing the percentage increase in the energy values required to arouse the threshold sensation for green at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

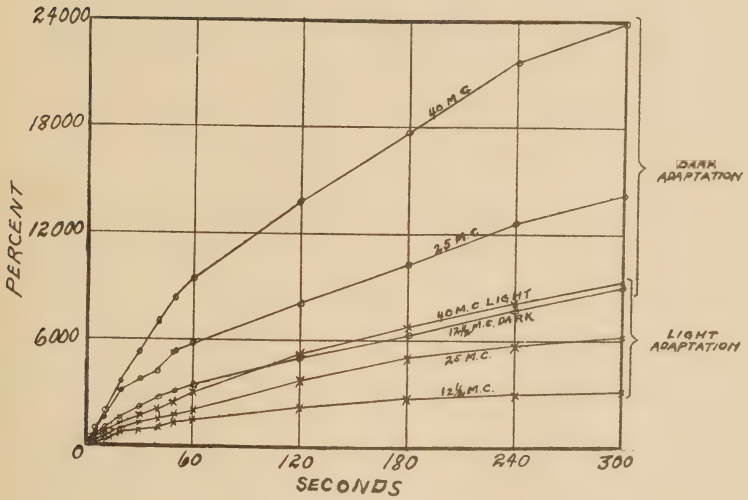

FIG. 25.

Showing the percentage increase in the energy values required to arouse the threshold sensation for blue at 12.5, 25, and 40 meter-candles for both dark and light adaptation.

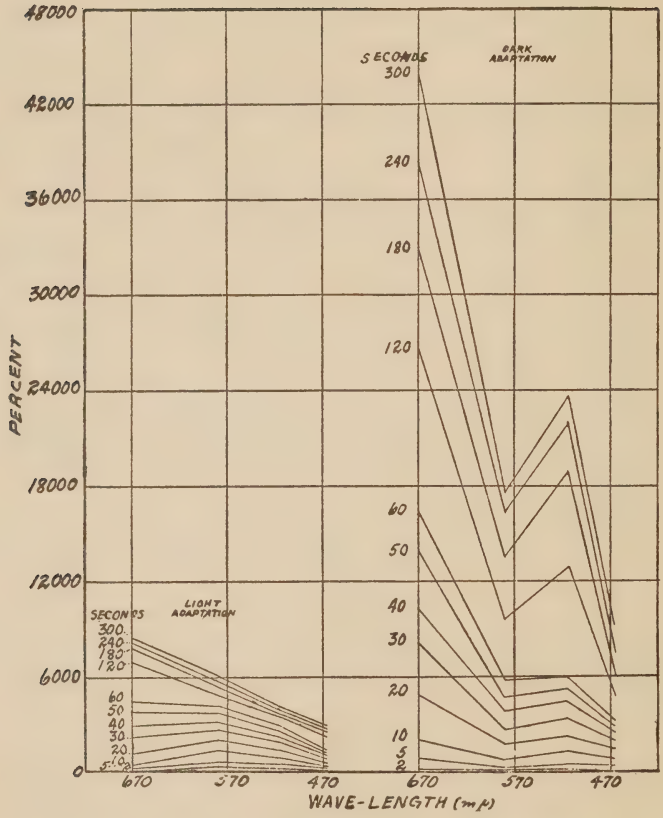

FIG. 26.

Showing the percentage increase in the energy values required to arouse the threshold sensation for each color and each length of exposure for both light and dark adaptation. The lights were made equal photometrically at 12.5 meter-candles.

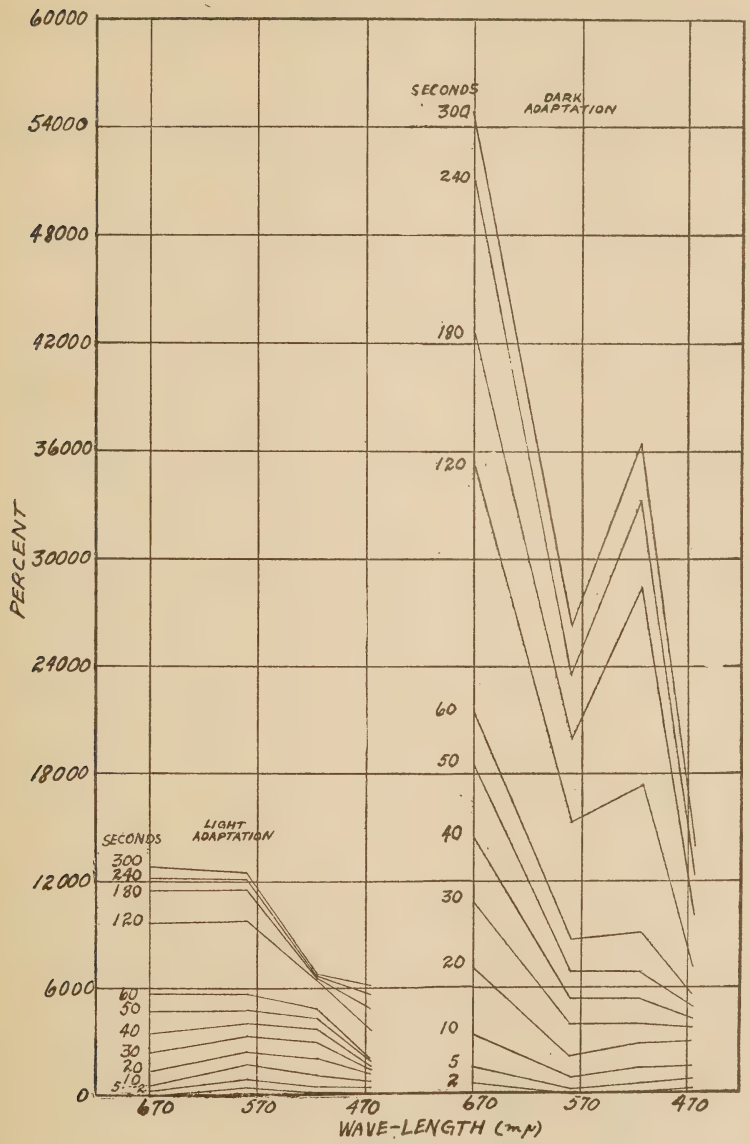

FIG. 27.

Showing the percentage increase in the energy values required to arouse the threshold sensation for each color and each length of exposure for both light and dark adaptation. The lights were made equal photometrically at 25 meter-candles.

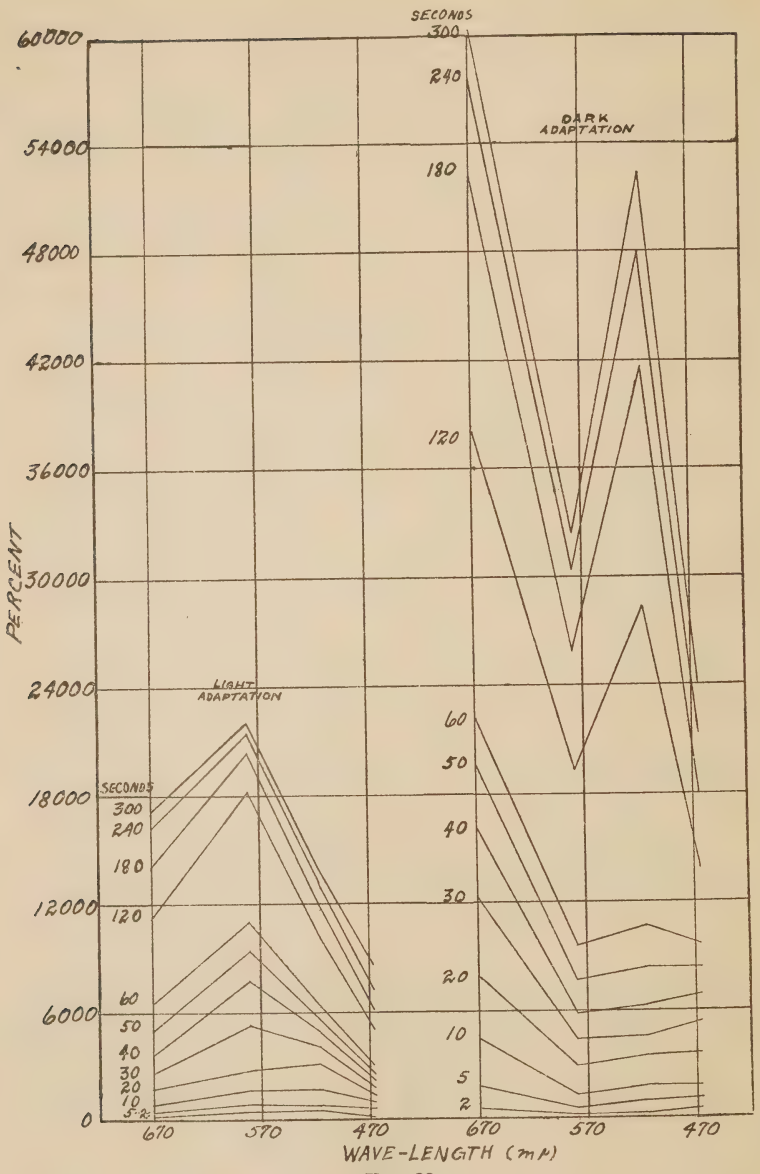

FIG. 28.

Showing the percentage increase in the energy values required to arouse the threshold sensation for each color and each length of exposure for both light and dark adaptation. The lights were made equal photometrically at 40 meter-candles.

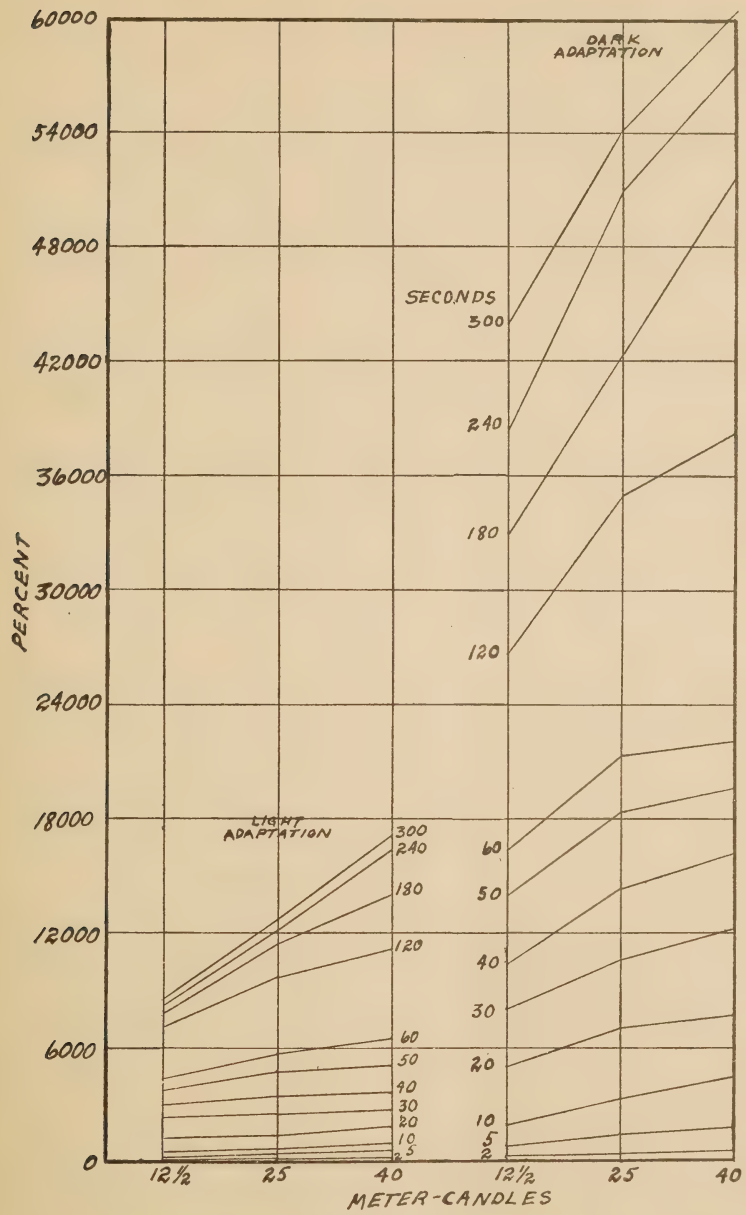

FIG. 29.

Showing the percentage increase in the energy values required to arouse the threshold sensation for red at each photometric intensity and each length of exposure for both dark and light adaptation.

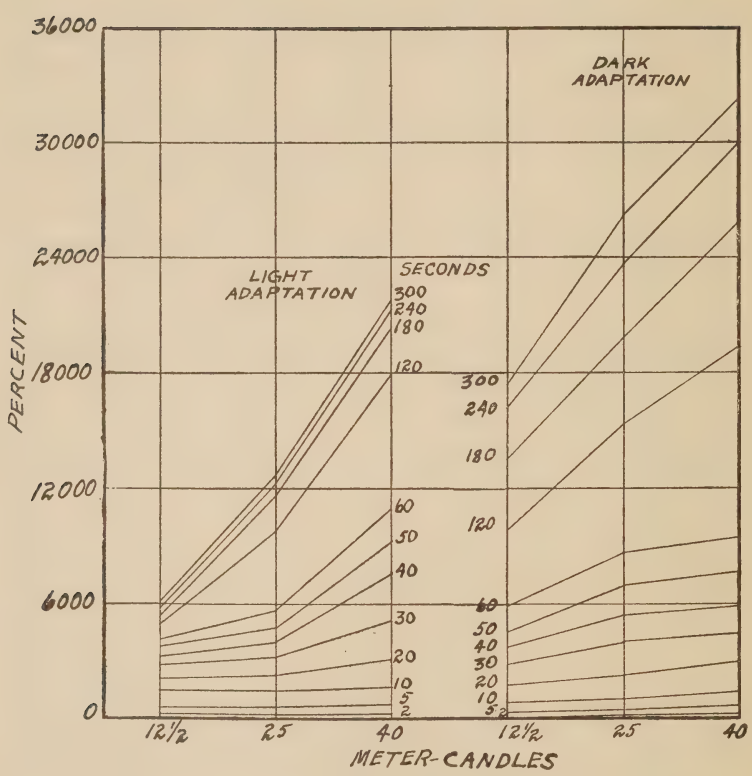

Fig. 30.

Showing the percentage increase in the energy values required to arouse the threshold sensation for yellow at each photomethic intensity and each length of exposure for both dark and light adaptation.

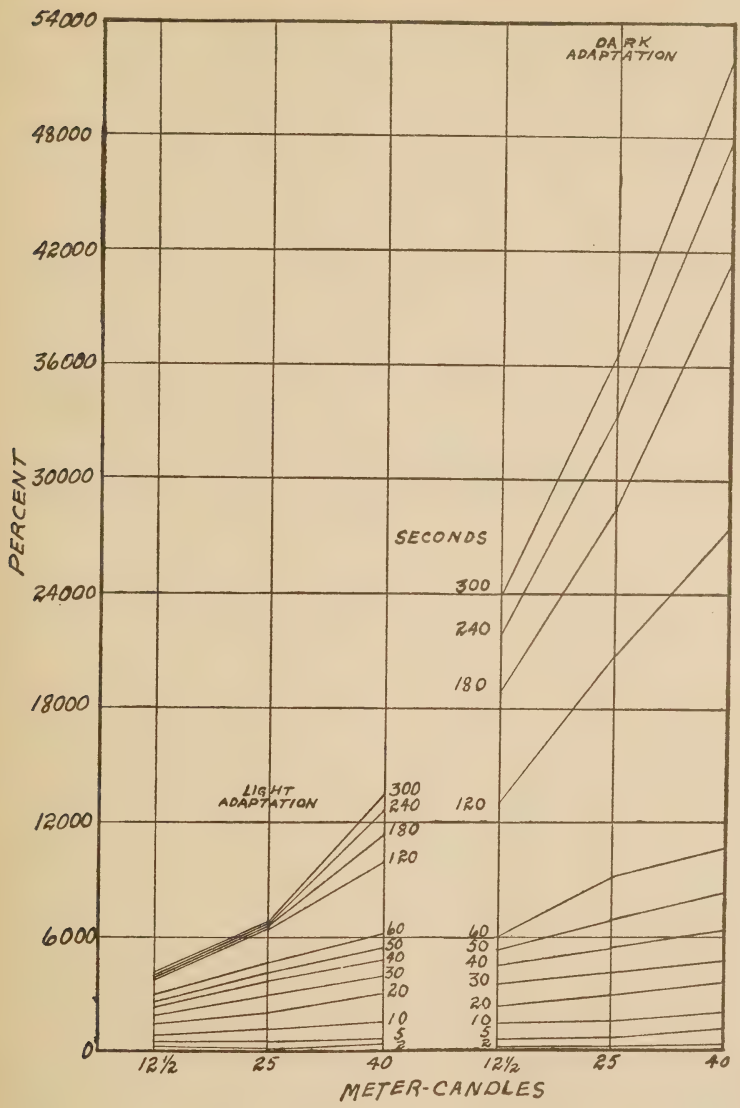

FIG. 31.

Showing the percentage increase in the energy values required to arouse the threshold sensation for green at each photometric intensity and each length of exposure for both dark and light adaptation.

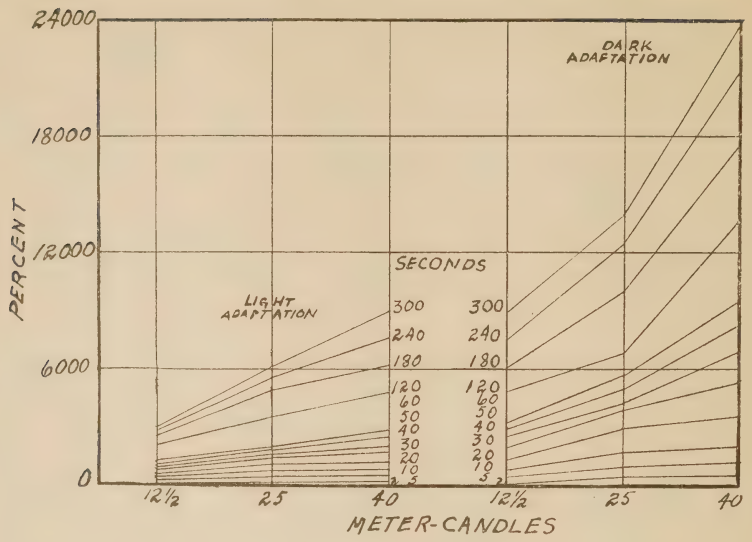

Fig. 32.

Showing the percentage increase in the energy values required to arouse the threshold sensation for blue at each photometric intensity and each length of exposure for both dark and light adaptation.

B. The Lights Made Equal in Saturation

It has been claimed by Sheppard that saturation is the most important determinant of the rate of chromatic adaptation. This claim, it may be noted, has in no way influenced our choice of lights equalized in saturation for one set of conditions for our experiments. As already stated, this choice was made because of its relation to the subject of colorimetry. To have made the choice in order to determine the relative importance of saturation as a factor would have been futile. That is, it would not have been possible to determine the effect of saturation in isolation from other factors since the saturation of a spectrum color cannot be changed independent of its brightness without introducing impurity as a complicating factor. Sheppard's conditions, it may be pointed out, did not even approximate those needed for isolating saturation as a factor or for drawing his conclusions.

Saturation of a color of any given wave-length is a subjective

aspect of its intensity. Just what is meant by it as the most important determinant of chromatic adaptation is not easily understood. A probable interpretation is that the intensity which arouses the sensation of greatest saturation is the intensity for any given wave-length which produces the fastest rate of adaptation. That this is far from true is shown by the results of our first set of experiments. In these experiments the spectrum colors used as stimuli were equalized at 12.5, 25, and 40 meter-candles. At these intensities all of the colors were far above their point of maximum saturation. The colors at 25 meter-candles were thus less saturated than at 12.5 and the colors at 40 meter-candles were less saturated than at 25; yet the rate of adaptation at 40 meter-candles was much faster than at 25 and the rate at 25 meter-candles much faster than at 12.5. Correctly interpreted here the determinant is physical intensity, not saturation. Saturation and birghtness are merely the subjective aspects of physical intensity. They are by no means determinants of the rate of adaptation; rather, together with rate of adaptation, they are, for a given group of wave-lengths, determined by the physical intensity. With respect to the physical intensity they stand in the relation of effect to cause.

The phenomenon of chromatic adaptation is only a series of diminishing saturations occurring in sequence. As a function of time, saturation starts at a minimum or threshold value, rises quickly to a maximum and again sinks to a minimum. The stimulus stands in a causal relation to all of the members in this series of changes, not one member of the series to another. The determinants both for the rate of rise and decay are therefore neither saturation nor brightness but such factors as physical intensity, wave-length, and composition of light, purity of light, and state of adaptation of the eye. The ascription of causal importance to brightness and saturation doubtless is a resultant of the failure, so often encountered, to distinguish between the stimulus and its subjective aspects or the aspects of the sensations which it arouses.

It is important and interesting, however, to determine the relative rates of adaptation for lights of the intensities which give

equal saturation inasmuch as the equalizations made in colorimetry are in terms of hue and saturation. In making both the photometric and colorimetric equalization or balance, too little attention has been given to time as a determining factor in the value of the balance obtained. A balance of either type made for one length of exposure to the eye cannot be expected to hold for any other length of exposure when the lights compared differ in composition. Just as we have studied the rate of rise and decay of sensation in relation to photometry, so should we make both of these studies in relation to colorimetry.

1. *Loss of Sensitivity.*

In the present series of experiments all of the colors were made equal in saturation to the yellow at 25 meter-candles. Yellow was chosen as the standard because it is the least saturated of the colors. The process of equalization consisted in reducing the saturation of the remainder of the colors until they equaled that of the yellow. Higher intensities were not used because of the low saturation of the colors at these intensities.

The loss of chromatic sensitivity as expressed by the logarithms of the reciprocals of the threshold energy values is presented in Table XXVIII for light adaptation and Table XXIX for dark adaptation. Curves based on the results in these tables are given

TABLE XXVIII. Light Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal in saturation to yellow (579 mμ) at 25 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	10.243	11.817	11.476	10.805
2	9.476	11.216	10.297	10.416
5	9.269	10.893		10.274
10	9.261	10.588		10.126
20	9.215	10.412		9.990
30	9.198	10.291		9.937
40	9.191	10.199		9.927
50	9.183	10.123		9.922
60	9.182	10.042		9.920
120		9.824		
180		9.750		
240		9.729		
300		9.716		

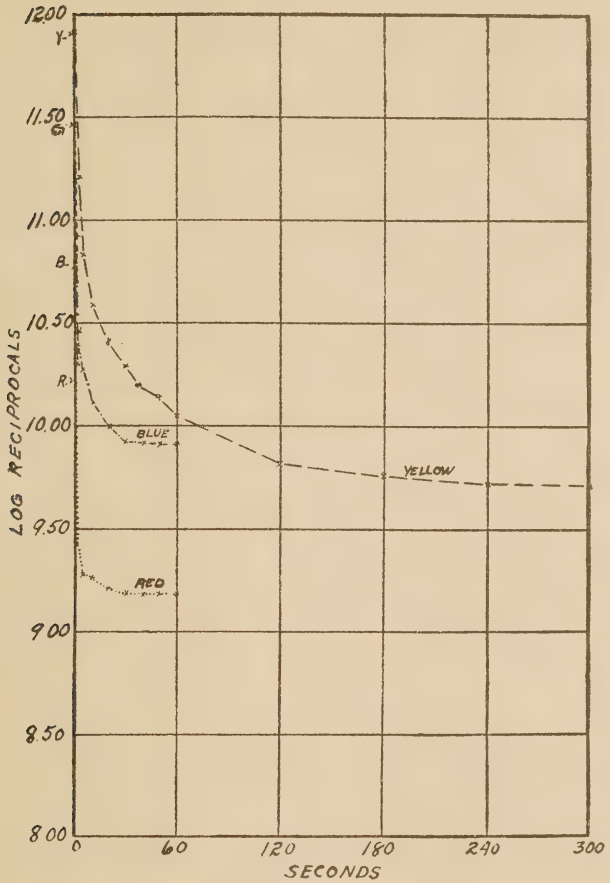

FIG. 33.

Showing loss of sensitivity under dark adaptation for spectrum red, yellow, green, and blue, made equal in saturation to yellow (579 mμ) at 25 meter-candles.

in Figures 33 and 34. These results are most certainly not compatible with the conclusions drawn by Sheppard.

If saturation were the dominant factor governing the rapidity of adaptation, all of the colors should show somewhere near the same rate of adaptation when stimuli of equal saturation are used. This is far from true particularly in case of light adaptation. Green, when made equal in saturation to the yellow at 25 meter-candles, is seen to have lost all of its color after a few seconds of exposure; and blue and red after an exposure of one minute. Yellow alone held its color throughout the entire period of five minutes. In the case of dark adaptation, all of the stimuli retained their color throughout the five-minute period, but during this time the loss of sensitivity was by no means equal. In these experiments the influence of other factors than saturation is shown strongly. The outstanding factors are wave-length and state of adaptation of the eye, which were not affected at all by the equalization in saturation; and physical intensity, which was affected considerably by this equalization. The effect of state of adaptation on the rapidity of chromatic adaptation is particularly noticeable in these results. An important factor in this effect doubtless is the influence of state of adaptation as a determinant of the intensities at which the colors are seen as equally saturated; *i.e.*, the same relative intensities were not required to give equal

TABLE XXIX. Dark Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal in saturation to yellow (579 mμ) at 25 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	11.346	12.678	12.797	11.696
2	10.528	12.336	12.458	11.301
5	10.303	12.077	12.249	11.053
10	10.040	11.638	12.037	10.795
20	9.734	11.299	11.827	10.477
30	9.544	11.066	11.704	10.289
40	9.419	10.930	11.614	10.167
50	9.329	10.822	11.554	10.086
60	9.284	10.730	11.518	10.050
120	9.253	10.486	11.430	10.009
180	9.240	10.374	11.394	9.983
240	9.233	10.297	11.381	9.976
300	9.231	10.256	11.371	9.972

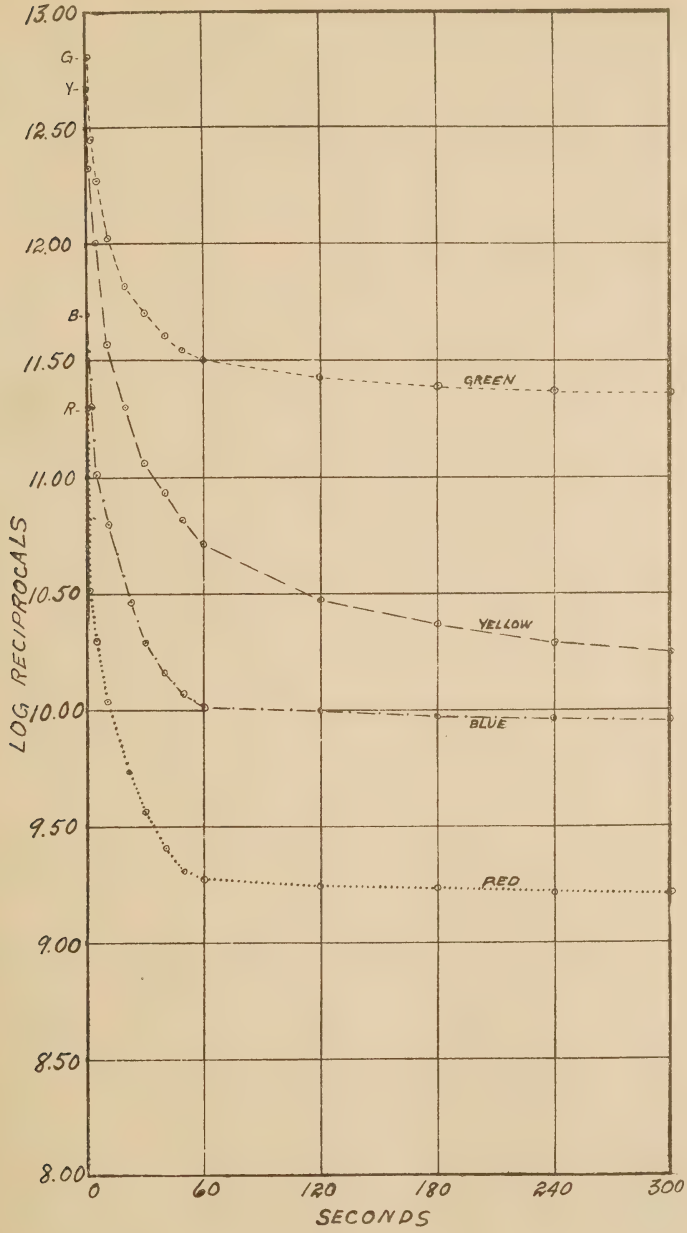

FIG. 34.

Showing loss of sensitivity under dark adaptation for spectrum red, yellow, green, and blue, made equal in saturation to yellow (579 mμ) at 25 meter-candles.

saturations with the eye light adapted as are needed when it is dark adapted. The true effect of state of adaptation on the rapidity at which the eye loses its sensitivity to color is shown, as in case of all of the other factors, in the experiments in which the stimuli were made equal in physical intensity or energy.

2. Percentage Increase of Light Required to Arouse the Threshold Sensation.

The curves in Figures 35 and 36, in which percentage increase in energy required to arouse the threshold sensation are plotted against length of exposure, show even more clearly the truth about the points just discussed. These figures are based on the results given in Tables XXX and XXXI. In particular they show the importance of physical intensity as a determinant of the rapidity of adaptation rather than the subjective aspect, saturation. For example, in order to make the colors equal in saturation to the yellow, their physical intensity had to be reduced by large amounts. As compared with the intensities at which all were equally bright at 25 meter-candles, for the dark-adapted eye, red had to be reduced approximately to 1/15 and green 1/72 of that intensity. An examination of Figure 20, which gives in percentages the comparative rates of loss of sensitivity for the dark-adapted eye when made equal in brightness at 25 meter-candles for the four colors, shows that red adapted much faster than green, green

TABLE XXX. Light Adaptation

Showing percentage increase in the energy values of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in saturation to yellow (579 mμ) at 25 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	483	298	1409	144
5	739	738		240
10	858	1594		376
20	964	2440		553
30	1010	3254		637
40	1027	4048		657
50	1046	4848		664
60	1050	5852		667
120		9742		
180		11578		
240		12136		
300		12497		

TABLE XXXI. Dark Adaptation

Showing percentage increase in the energy values of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in saturation to yellow (579 mμ) at 25 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values—— Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	559	119	118	149
5	1097	299	253	339
10	1927	995	475	696
20	3996	2294	833	1556
30	6238	3989	1141	2401
40	8347	5474	1423	3275
50	10323	7092	1649	3981
60	11455	8758	1799	4329
120	12299	15470	2232	4771
180	12676	20040	2432	5069
240	12898	23943	2508	5169
300	12943	26323	2521	5194

much faster than yellow, and yellow much faster than blue. After the reductions were made to bring them to equal saturation, red for a part of the five-minute period showed a faster rate of adaptation than yellow, and for the remainder of the time a slower rate; yellow adapted much faster than either blue or green; and green, which suffered much the greatest reduction of intensity in the process of equalization of saturation, gave correspondingly the

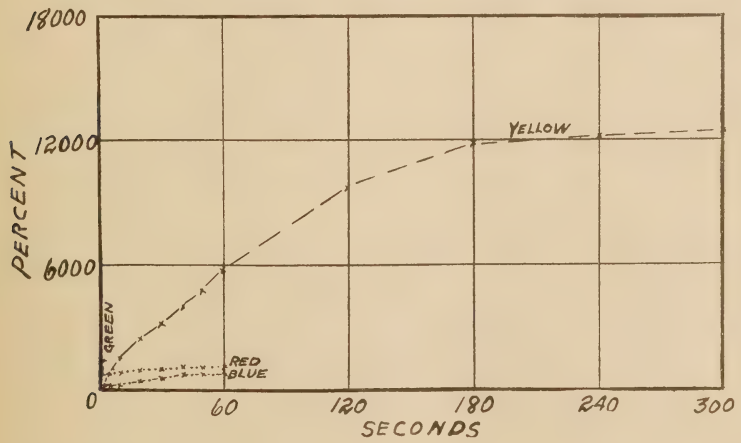

FIG. 35.

Showing the percentage increase in the energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal in saturation to yellow (579 mμ) at 25 meter-candles, for light adaptation.

slowest rate of adaptation. A glance at these two sets of curves (Figures 20 and 36) certainly shows beyond dispute that physical intensity is a more important determinant of rate of adaptation for any given group of wave-lengths than saturation.

It is not to be understood here, however, that the claim is made that physical intensity is the only factor that influences the rapidity of adaptation. If that were true the stimulus which has the greatest physical intensity would always produce the fastest rate of adaptation. It is only one of a group of factors which affect the rate of adaptation. So far as we know, rate of adaptation is an irregular function of four variables: wave-length, intensity, time of exposure, and state of adaptation of the eye.

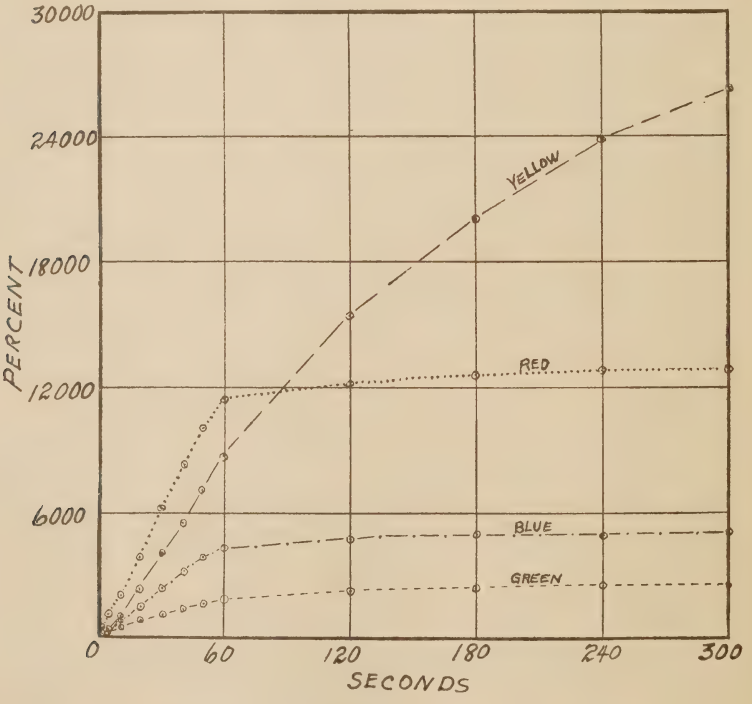

Fig. 36.

Showing the percentage increase in the energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal in saturation to yellow (579 mμ) at 25 meter-candles, for dark adaptation.

In Figure 37 curves are given showing a cross comparison of the percentage increase of energy required to arouse the threshold sensation for each color for each length of exposure used. In these curves wave-length of light is plotted on the horizontal

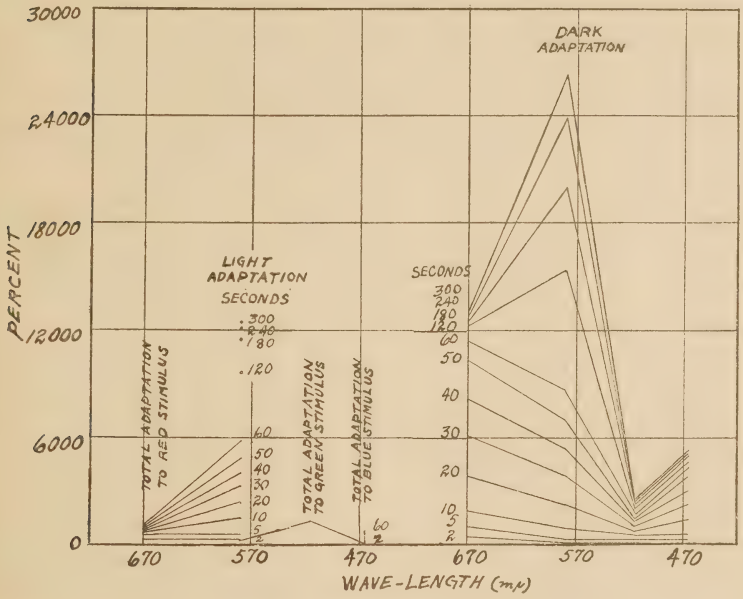

Fig. 37.

Showing the percentage increase in the energy values required to arouse the threshold sensation for each color and each length of exposure for both light and dark adaptation. The lights were made equal in saturation to yellow (579 mμ) at 25 meter-candles.

coördinate and percentage increase of energy required to arouse the threshold sensation on the vertical coördinate. This form of presentation of the data also shows very clearly that colors of equal saturation do not adapt at the same rate.

C. Lights Made Equal in Energy

In the preceding sections results have been given for four spectrum colors at intensities which gave equal photometric values or brightnesses and equal saturations. These equalizations in

terms of subjective aspects of light or power to arouse sensations were made for the practical reasons already given. A true investigation of the eye's selectiveness or inequality of response to light or of a selectiveness in this change of response as a function of length of exposure, obviously cannot be made with lights equalized in terms of any of its subjective aspects or powers to arouse sensation. That is, such an investigation demands that the method of equalizing or rating the lights be entirely independent of its power to arouse the response investigated. For this reason the lights in one set of experiments were rated in terms of their physical or energy values.

Experiments performed in the Bryn Mawr laboratory have shown that the responses of the eye are selectively a function of three interacting variables: wave-length, intensity, and time of exposure. Previous to the present investigation, however, this selectiveness has been shown only for lengths of exposures less, equal to, and slightly greater than the time required for the sensation to reach its maximum value. The present investigation was planned to determine the selectiveness of response for lengths of exposure greater than is required to give the maximum sensation. The results, as will be seen, not only show that for long exposure times the response of the eye is a function of three interacting variables but in addition they show that there is a fourth variable, the state of brightness adaptation.

1. *Loss of Sensitivity.*

The results of this investigation showing loss of sensitivity are given in Tables XXXII–XXXIII and in Figures 38–39. The following points may be noted: (1) Although the stimuli were all of equal physical intensity, the eye lost its sensitivity to them at very different rates. For example, in the experiment under light adaptation it had completely lost its sensitivity to the red stimulus at the end of one minute, while it retained sensitivity to the other colors to the end of the five-minute period. In the experiments under dark adaptation the difference in the effect of wave-length on the rate of adaptation was not so great. The eye lost its sensitivity to the different colors at different rates but it had retained

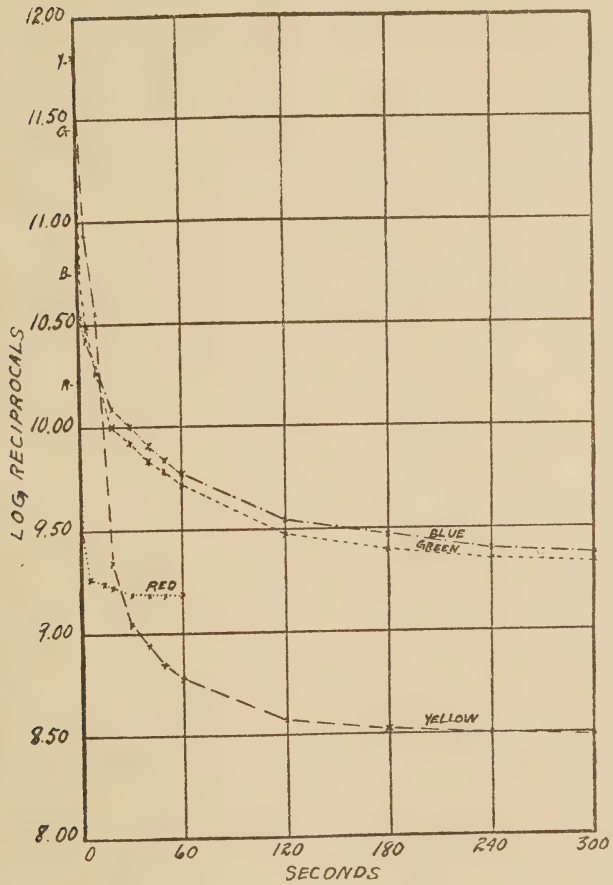

FIG. 38.

Showing loss of sensitivity under light adaptation for spectrum red, yellow, green, and blue, made equal in energy to green (515 mμ) at 40 meter-candles.

some sensitivity to all of them at the end of the five-minute period. (2) The high degree of selectiveness of sensitivity to the combined effects of wave-length and time of action on the eye is further shown by the following changes which occur in the relative sensitivity of the eye to the various wave-lengths at different times throughout the adaptation period. For example, the order of ranking as to sensitivity for the fresh eye under light adaptation was, from greatest to least, yellow, green, blue, and red. After 24 seconds of exposure it had changed to blue, green, red,

TABLE XXXII. Light Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal in energy to green (515 mμ) at 40 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	10.243	11.817	11.476	10.805
2	9.476	11.200	10.761	10.548
5	9.269	10.942	10.478	10.416
10	9.261	10.562	10.269	10.291
20	9.215	9.354	9.976	10.095
30	9.198	9.100	9.871	10.000
40	9.191	8.933	9.799	9.865
50	9.183	8.857	9.741	9.788
60	9.182	8.792	9.678	9.726
120		8.498	9.473	9.553
180		8.525	9.413	9.483
240		8.505	9.367	9.419
300		8.498	9.341	9.398

TABLE XXXIII. Dark Adaptation

Showing the chromatic sensitivity of the eye in terms of the logarithm of the reciprocals of the energy values required to arouse the threshold sensation. The fatiguing lights were made equal in energy to green (515 mμ) at 40 m.c.

Fatigue period in seconds	Logarithms of the reciprocals of threshold energy values			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
0	11.346	12.678	12.797	11.696
2	10.528	12.200	12.195	11.261
5	10.303	11.869	11.739	10.925
10	10.040	11.568	11.496	10.738
20	9.734	11.261	11.253	10.521
30	9.544	11.045	11.110	10.358
40	9.419	10.948	10.979	10.282
50	9.329	10.840	10.864	10.247
60	9.284	10.713	10.761	10.213
120	9.253	10.432	10.341	10.061
180	9.240	10.304	10.189	9.964
240	9.233	10.242	10.113	9.893
300	9.231	10.200	10.076	9.849

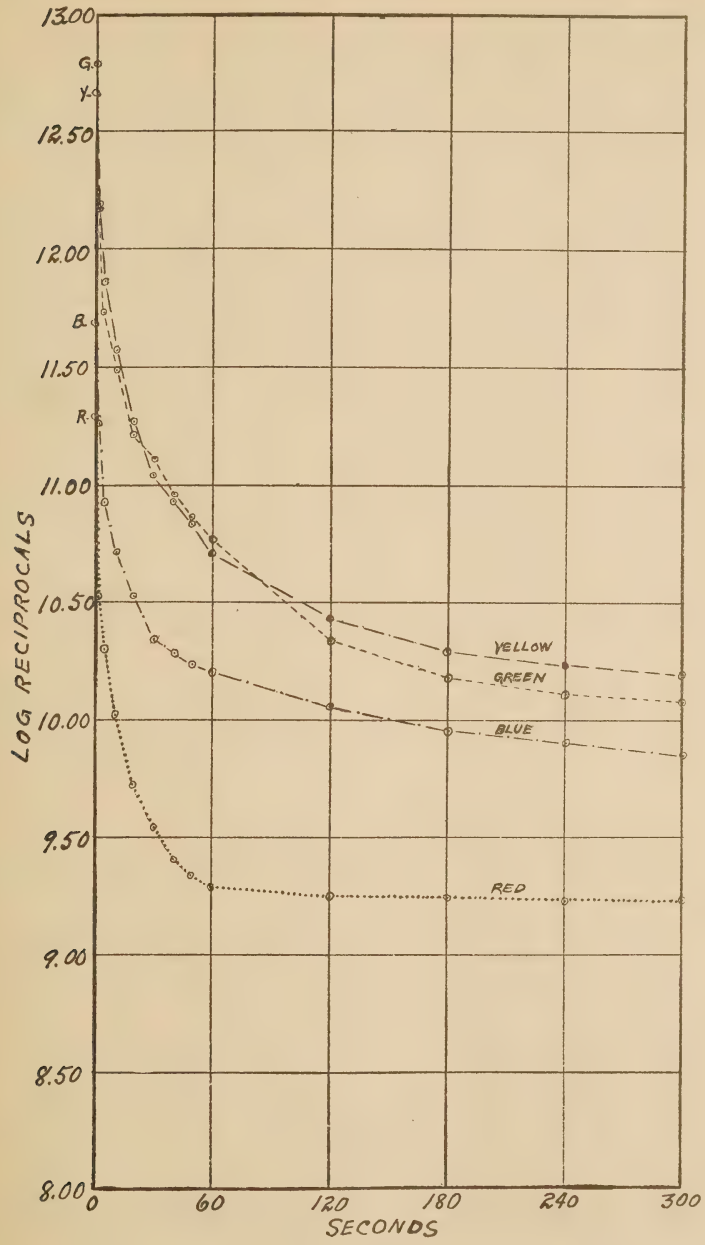

Fig. 39.

Showing loss of sensitivity under dark adaptation for spectrum red, yellow, green, and blue, made equal in energy to green (515 mμ) at 40 meter-candles.

and yellow. The reversal in the relation of sensitivity to blue and yellow as the result of time of exposure is quite striking. For dark adaptation the order of sensitivity for the fresh eye was green, yellow, blue, and red. In the process of adapting, the eye changed its ratio of sensitivity to green and yellow three times. At the end of two seconds it became more sensitive to yellow than to green; at the end of 24 seconds more sensitive to green than to yellow, and at the end of 87 seconds again more sensitive to yellow than to green, which relation of sensitivity it retained throughout the remainder of the period. The order of ranking of sensitivity to blue and red remained the same throughout the five-minute period although the relative rate of loss of sensitivity changed throughout this period, as will be seen in the curves in the next section.

2. Percentage Increase of Light Required to Arouse the Threshold Sensation.

The data for this form of treatment of the results are given in Tables XXXIV–XXXV and Figures 40–42. These data show the selectiveness of the adaptation process to time of exposure or the selectiveness of sensitivity to length of stimulation more clearly than those of the preceding section. An examination of the shape of any given curve shows the irregular change in the eye's loss

TABLE XXXIV. Light Adaptation

Showing percentage increase in the energy values of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in energy to green (515 mμ) at 40 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	483	314	419	80
5	739	650	597	144
10	858	1692	1510	226
20	964	2795	3050	412
30	1010	5110	3917	528
40	1027	7544	4635	766
50	1046	8987	5322	938
60	1050	10496	6174	1097
120		17384	9957	1684
180		19483	11452	1991
240		20532	12737	2322
300		20730	13545	2444

of sensitivity with increase in time of exposure of the eye and a comparison of the shapes of the different curves, the selective nature of the sensitivity to wave-length, and the change in this selectiveness as a function of time. That is, it will be seen that

TABLE XXXV. Dark Adaptation

Showing percentage increase in the energy values of light at the eye required to arouse the threshold sensation. The fatiguing lights were made equal in energy to green (515 mμ) at 40 m.c.

Fatigue period in seconds	——Percentage increase of threshold energy values——			
	Red 670 mμ	Yellow 579 mμ	Green 515 mμ	Blue 466 mμ
2	559	200	238	172
5	1097	542	1047	490
10	1927	1190	1899	805
20	3996	2509	3568	1397
30	6238	4194	4759	2077
40	8347	5284	6458	2495
50	10322	6759	8465	2803
60	11455	9139	10784	3032
120	12299	17800	28529	4299
180	12676	23514	41633	5368
240	12898	27180	47966	6362
300	12943	29940	52543	7008

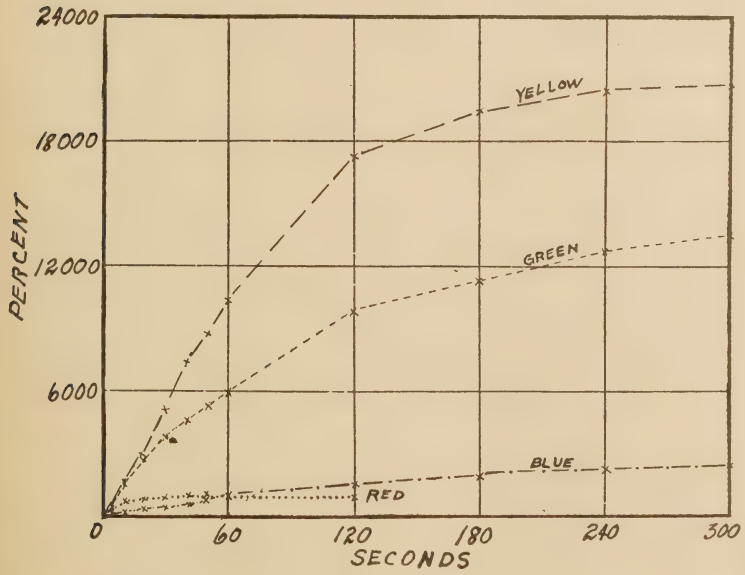

FIG. 40.

Showing the percentage increase in the energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal in energy to green (515 mμ) at 40 meter-candles, for light adaptation.

the chromatic sensitivity of the eye is not only very different for the different wave-lengths, but that the amount of this difference changes very irregularly with the time of action on the eye. The amount of change in this selectiveness to wave-length can be determined only by using equal amounts of energies of light as was done in these experiments.

These tables and curves show the following facts: (1) The chromatic sensitivity of the eye is not only very different for the different wave-lengths of light but the amount of this difference changes very irregularly with time of action on the eye. (2) Not only is the sensitivity of the eye greater under dark than under light adaptation, but the rate of loss of sensitivity is faster. (3) Under light adaptation the eye loses its sensitivity faster to yellow than to green. Up to 60 seconds it loses its sensitivity faster to red than to blue, and from that time on to the end of the five-minute period faster to blue than to red. (4) Under dark adaptation the loss of sensitivity is faster in order from greatest to least for red, green, yellow, and blue, for the first 60 seconds; from that time on to the end of the five-minute period the order is green, yellow, red, and blue. (5) The order of rate of loss of sensitivity seems to sustain some relation to the sensitivity of the fresh eye. The following examples of this relation may be noted: (a) The sensitivity of the fresh eye and also the rate of loss of sensitivity are greater for dark than light adaptation; (b) the sensitivity of the light-adapted eye is in order from greatest to least, yellow, green, blue; the sensitivity of the dark-adapted eye, green, yellow, blue. In both cases the rate of loss of sensitivity follows the same order as the initial sensitivity. For certain periods of time red alone is found to be an exception to the rule.

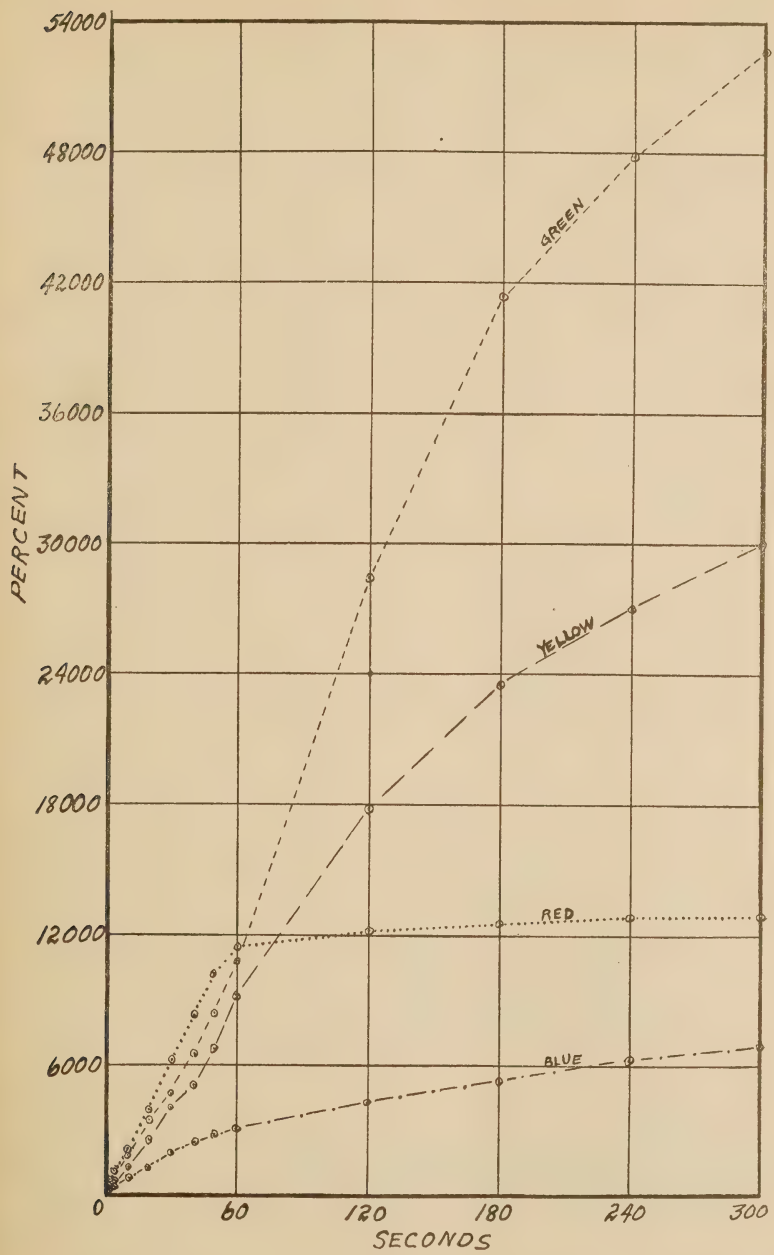

FIG. 41.

Showing the percentage increase in the energy values required to arouse the threshold sensation for red, yellow, green, and blue, made equal in energy to green (515 mμ) at 40 meter-candles, for dark adaptation.

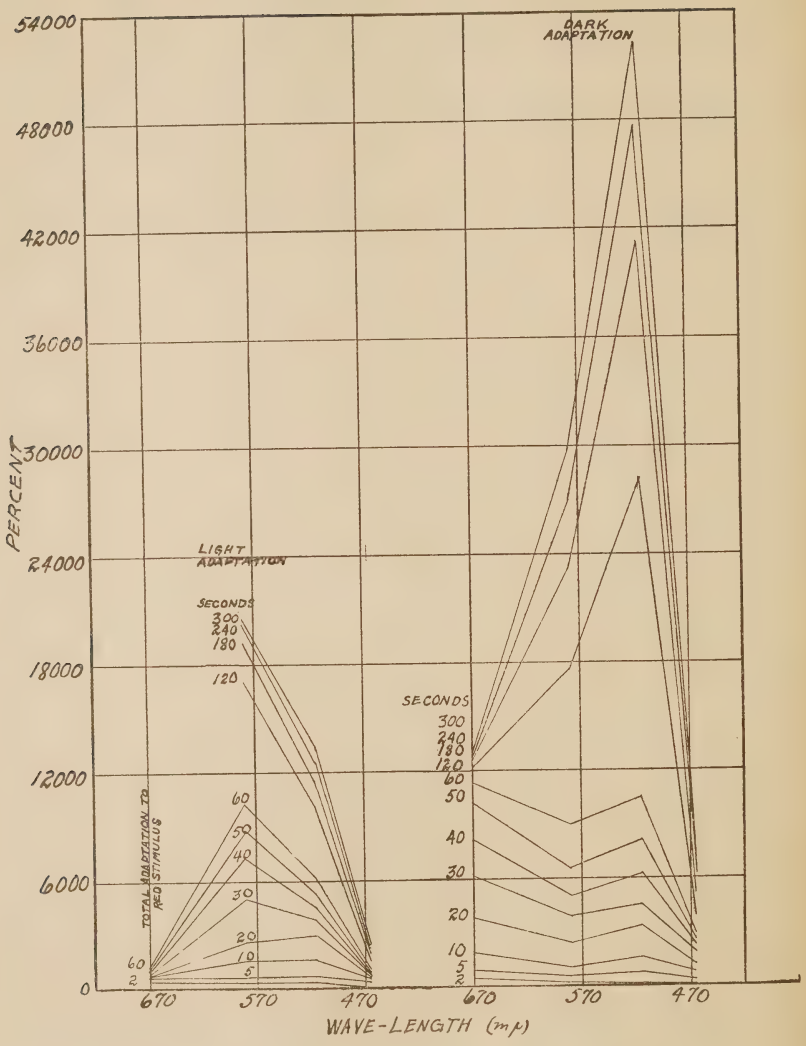

FIG. 42.

Showing the percentage increase in the energy values required to arouse the threshold sensation for each color and each length of exposure for both light and dark adaptation. The lights were made equal in energy to green (515 mμ) at 40 meter-candles.

V. SUMMARY

Although proper control of experimental conditions may increase the regularity in the responses of the eye, nevertheless there are certain characteristics of the retina as a receptor which causes it to be selective in its responses. Heretofore it has been shown with reference to exposures less, equal to, and slightly greater than the time required for the sensation to reach its maximum value, that the responses of the eye are selectively a function of three interacting variables: wave-length, intensity, and length of exposure. In the present study exposures of longer duration are used and the selectiveness or inequality of the eye's responses is investigated for the decay rather than the rise of sensation. This investigation has been extended to include also a fourth variable, namely, the condition of brightness adaptation.

Two possibilities of attacking the problem of decay of sensation were considered: the tracing of the sensation from maximum to minimum in just noticeably different steps and the determination of the change in the eye's power of response or sensitivity. The latter of these procedures was chosen for reasons noted in the Introduction.

Previous to this investigation a quantitative study of the loss of sensitivity as the result of fatigue has not been undertaken and there has been little attempt at any accurate control or even specification of the conditions employed. If a study of the loss of sensitivity is to be made quantitative up to the standard used in rating the sensitivity of the physical instruments, it must conform to the following requirement: Both terms involved in the expression for sensitivity, amounts of response, and amounts of stimulus must be numerically comparable. In case of the present investigation the amounts of stimulus are given in energy terms and comply therefore with the second of the above requirements for a quantitative study. The first is satisfied only within the limits of correctness of the assumption that thresholds of sensation represent equal amounts of response.

This quantitative study of decay of sensitivity both for light and dark adaptation has been made for lights equalized in all the ways, subjective and objective, in which amounts of colored light may be specified, namely, photometrically, radiometrically, and with reference to the saturation of the color sensation aroused. In order to obtain results for both light and dark adaptation, the investigation was conducted in a light room which was provided with curtains that could be drawn to give dark-room effects.

Spectrum lights, freed from the usual residual impurities by the use of specially selected filters and focussed at the eye, were used as stimuli. The energy of each light used was measured at the objective slit of the spectroscope by means of a linear thermopile in conjunction with a sensitive Thompson galvanometer and accessories.

The threshold of the same spectrum light which was used to induce loss of sensitivity was determined immediately at the end of each fatigue period. This was made possible by the introduction of a finely graded, adjustable sectored disc, rotated by a motor suspended by coiled springs from a point above and to one side of the center of the beam of light. By shifting the motor back and forth, the disc could be interposed in the path of the stimulus light or removed from it at will.

Before making the threshold determinations in the light room, 15 minutes were allowed for general brightness adaptation; in the dark room this period was increased to 30 minutes. The liminal threshold was first determined for the unfatigued eye and after this the threshold for the eye fatigued by the same light for periods varying in length from 2 to 300 seconds. From these thresholds the change in the sensitivity was determined. Since sensitivity may be considered as varying inversely as the amount of stimulus required to produce equal amounts of response, it may be represented in the present case by the reciprocal of the energy value of light required to arouse just noticeable chromatic sensation. This method of presenting the data makes possible an intercomparison of loss of sensitivity for the same wave-lengths of light at the different intensities employed because the initial threshold values in all of these cases are the same. However, it

does not permit of an intercomparison of loss of sensitivity for different wave-lengths because the different wave-lengths have different initial threshold values. In order to make comparison possible in the latter case the results have been presented also in terms of percentage increase in the energy value required to arouse the threshold sensation after the different periods of fatigue.

From these two methods of treating the results the following conclusions may be drawn:

(1) *For lights made photometrically equal at 12.5, 25, and 40 meter-candles.* (a) The sensitivity of the nonfatigued eye to the four colors used is in the order from greatest to least, yellow, green, blue, red. (b) Sensitivity decreases very rapidly at first but the decrease becomes slower with increase in length of fatigue period. (c) The order of ranking as to sensitivity for the four colors is not constant throughout the fatigue period of five minutes but the order of ranking for the initial and final sensitivity is the same. (d) The difference in sensitivity to yellow, green, and blue is decreased by increase in length of exposure, but the difference in sensitivity to these colors and to red is increased by increase of length of exposure. (e) The rate of adaptation increases with increase of photometric intensity. (f) Initial sensitivity is greater under dark than under light adaptation. This difference in sensitivity for the two states of adaptation, however, tends to become less as the length of the exposure is increased.

(2) *For lights equalized as to the saturation of the color sensation aroused.* (a) The rate of adaptation to color equalized as to saturation is very unequal. (b) The maximum rate of adaptation by no means occurs at that intensity of light which gives maximum saturation to the color sensation. The rate is comparatively slow for the colors at maximum saturation. The faster rates of adaptation come at intensities much higher than those required to give maximum saturation to the color sensation. Rate of adaptation is a function of the physical intensity of light, not of its subjective aspects, saturation and brightness. (c) The order of ranking for the colors as to rate of adaptation is very different when equalized as to saturation and when equalized as to brightness.

This is due to the fact that the relative intensities of the lights required to produce equal saturations are very different from those required to produce equal brightnesses. For example, as compared with the intensities at which all of the colors have equal brightness at 25 meter-candles, red had to be reduced to one fifteenth and green to one seventy-second of that intensity to give a saturation equal to that of yellow at 25 meter-candles. (d) The effect of state of adaptation of the eye is particularly noticeable on the results obtained with colors equalized in saturation. An important factor in this result doubtless is the influence of state of adaptation as a determinant of the intensities at which colors are seen as equally saturated, *i.e.*, the same relative intensities were not required to give equal saturation with the eye light adapted as were needed when it was dark adapted.

(3) *For lights made equal radiometrically.* (a) Fatigue to lights of equal physical intensity is not followed by equal loss of chromatic sensitivity to these lights. That is, the loss of sensitivity varies with the wave-length. (b) This difference in sensitivity changes irregularly with the time of action of the light on the eye. (c) Chromatic sensitivity is greater under dark than under light adaptation; also the rate of loss of sensitivity through fatigue is much greater under light than under dark adaptation. (d) The rate of loss of sensitivity for the various spectrum lights differs with difference in the length of the fatigue period. (e) With the exception of red, the rate of loss of sensitivity tends to follow the same order for the different colors as the initial sensitivity.

From the results of the experiments under the three sets of conditions the following more general conclusions may be drawn:

(1) The loss of sensitivity as a result of adaptation is an irregular function of four variables: wave-length, intensity, time of exposure, and general state of brightness adaptation of the retina.

(2) Saturation and brightness are factors in the result probably only in so far as they are functions of physical intensity. In fact, to say that saturation and brightness are causal factors in adaptation is practically the equivalent of saying that a phenome-

non is the cause of itself. That is, the phenomena of adaptation, so far as they can be observed, are just changes in the subjective aspects, saturation, brightness, and hue.

(3) The shape of the adaptation curve is not at all that of a typical fatigue curve. It is more closely what would be expected of an activity in which there is a rapid rise of a reverse or antagonistic process. The presence of this process was clearly demonstrated in the observations made in every determination of the threshold following the period of adaptation or fatigue; that is, the stimulus used to arouse the threshold response when subliminal in intensity was always sensed in the after-image or antagonistic color; when of a certain stronger intensity it was sensed as neutral or colorless; and when it was of supraliminal intensity it was sensed in its proper color. That the process should not reach a state of continuous equilibrium once the stage of neutrality is reached, *i.e.,* that there should be recurrence of color, should not be unduly disturbing to this point of view, for fluctuation in the activity of the process would be expected if for any reason there were changes either in the concentration of the visually active substance or in the amount of light acting on it. Changes in the concentration of the visual substance may be expected from the influence of eye-movement on the metabolism of the retina. The influence of eye-movement on the recovery of the sensitivity of the retina is a well known phenomenon which can be easily demonstrated. Changes in the amount of light acting on the part of the retina on which the image is formed are also bound to occur as a result of blinking, eye-movement both voluntary and involuntary, and fluctuations in the size of the pupil.

(4) The rate of adaptation seems to sustain a direct relation to the state of sensitivity of the retina. That is, the rate is fast at the beginning of the exposure and becomes progressively slower as the length of the exposure is increased. Also the rate of adaptation for the dark-adapted eye which has the higher initial sensitivity is much faster than for the less sensitive light-adapted eye. Further the colors to which the fresh eye is the most sensitive cause the more rapid loss of sensitivity.

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